EVALUATION OF WARM MIX ASPHALT PERFORMANCE INCORPORATING HIGH RECLAIMED ASPHALT PAVEMENT CONTENT

A thesis submitted in partial fulfilment of the requirements for the Degree of

Master of Engineering in Transportation

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University of Canterbury

2016

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ACKNOWLEDGEMENTS

I would like to thank the New Zealand Government for giving me a scholarship to fulfil my Master’s degree at the University of Canterbury.

To my supervisor, Associate Professor Mofreh Saleh, thank you very much for your support, advice, and encouragement during my research. I also appreciate your encouragement and support in publishing articles in journals and presenting at international conferences. My appreciation also goes to Professor Alan Nicholson, Dr Glen Koorey and Dr Tony Sze for their knowledge during my Master’s study.

I would like to thank John Kooloos, technician of the Transportation Laboratory, University of Canterbury, and Milad Ghorban Ebrahimi, a former PhD student in pavement engineering, for their kind help during my project. I also gratefully acknowledge the staff from Fulton Hogan. To John Forrest, Martin Clay, Glynn Holleran and their staff, thank you for the material donation and helpful advice during the research; thanks to Max Burford and Irina Holleran for helping running the RAP property tests. I gratefully acknowledge Damien Hond and Arizona Chemical for the additives donation. Without those people, none of the work could have been done.

I would like to say thanks to staff of the Development Team: Craig Forman, Shelley Chappell, and others. Thank you for your friendly and kindly help from the very early days I arrived in New Zealand. My further thanks to the Academic Skills Centre for helping me with my English skills. Two years were very long without my friends around. Thank you all for the good times.

To my family, thank you very much for your love, support and encouragement.

ABSTRACT

Warm mix asphalt (WMA) has gradually become more popular in the roading industry, because, compared to hot mix asphalt (HMA), WMA can bring numerous benefits, such as lower energy consumption, lower emissions, and greater ability to incorporate a high proportion of reclaimed asphalt pavement (RAP) in the mixtures. Incorporating RAP in WMA can increase the sustainability benefits and enhance the performance of WMA. This study investigated the performance of WMA by adding RAP in different proportions, from 0 up to 70% by mass of WMA. The performance of mixtures was compared with a control HMA. One type of binder, 80/100 penetration grade, and two types of additives were use: a chemical warm mix additive and a rejuvenator, namely, Evotherm and Sylvaroad^{TM} RP1000, respectively. Tests were done on the binder's viscosity and the mechanical performance of mixtures such as moisture resistance, fatigue cracking, and rutting resistance. In this study, the semi-circular bending test was investigated to further study its applicability in asphalt pavement testing.

Results from laboratory tests showed that the two additives reduced the viscosity of the binder. Mixtures with the chemical additive (Evotherm) performed better than other mixtures in terms of moisture resistance. Only the WMA mixture with the Sylvaroad rejuvenator showed a higher number of cycles to fatigue failure than the control HMA. For rutting resistance, the increase in RAP proportion greatly improved the performance of WMA mixtures. WMA without RAP had a lower number of cycles to reach maximum rut depth than the HMA. All WMA-RAP mixtures showed considerably better rutting resistance than the HMA. The study of semi-circular bending test showed that the notch depths from 5 to 15 mm are suitable for 100 mm diameter samples. The indirect tensile strengths yielded by the semi-circular test and those from the indirect tensile method could be convertible.

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Lu D. X. and Saleh M. F. (2016) Comparison of Semi-circular bending test, fatigue test and indirect tensile test methods. (in final stage preparation, to be submitted to International Journal of Pavement Research and Technology)

Lu D. X. and Saleh M. F. (2016) Evaluation of Warm Mix Asphalt Performance Incorporating High Content. *Canadian Journal of Civil Engineers.* http://dx.doi.org/10.1139/cjce-2015-0454.

Lu, D. X. and Saleh, M. F. (2016) Laboratory Evaluation of Warm Mix Asphalt Incorporating High Rap Proportion by Using Evotherm and Sylvaroad Additives. *Construction and Building materials.* Volume 114, 1 July 2016: Pages 580–587. http://dx.doi.org/10.1016/j.conbuildmat.2016.03.200

Lu, D. X. and Saleh M.F. (June-2016) Evaluation of Mechanical properties of a New Warm-Mix Asphalt Using Sylvaroad Additive. *6th Annual International Conference on Civil Engineering, Athens, Greece*. (Oral presentation – Conference contribution - Accepted)

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CHAPTER 1: INTRODUCTION

1.1 Context

Warm mix asphalt (WMA) technologies have been developed since the late 1990s (Yang et al., 2012) and have gradually become popular in the roading industry. WMA products are usually produced at temperatures between 110°C and 142°C (D'Angelo et al., 2008), which are relatively lower than the mixing temperatures of conventional hot mix asphalt (HMA), usually ranging from 140°C to 180°C (D'Angelo et al., 2008).

At lower mixing temperatures, WMA significantly reduces emissions compared to traditional HMA (Gandhi, 2008), which benefits the environment. Moreover, WMA allows compaction at cooler temperatures while still assuring workability of mixtures, which extends both the haulage time (Zhang, 2010) and the construction season, especially for cold weather countries. Compaction of WMA at lower temperatures requires less time to cool, reducing the time before the next layer can be placed or reducing the time the road can be opened to traffic (Zaumanis, 2010). WMA also saves fuel owing to its lower mixing temperatures.

Each year, millions of tons of asphalt pavements are removed all over the world. In Europe alone, more than 50 million tons of old asphalt concrete are removed annually (Dinis-Almeida et al., 2012). The recycling of old asphalt pavement can bring numerous benefits, such as reducing the use of new materials, saving space owing to mitigating landfill requirement for old asphalt pavement, and lowering the costs of the product. In recent years, the incorporation of reclaimed asphalt pavement (RAP) in WMA has become an important topic for researchers and practitioners since RAP can increase the sustainability benefits and enhance the performance of WMA compared to HMA.

1.2 Objectives

Although using WMA and RAP is promising and profitable, studies of WMA with high RAP as a structural asphalt layer in the upper part of the pavement structure, which is subjected to high stresses, is limited worldwide and in particular in NZ and Australia. Therefore, this study is necessary to investigate the feasibility of using high RAP content in warm mix asphalts. The objectives of this study are listed below:

- investigate the effect of warm mix additives in warm mix asphalt
- study the effect of RAP in WMA by evaluating the mechanical performance of WMA and WMA-RAP mixtures, and compare with control mix of HMA
- investigate methods to increase the RAP content in WMA
- investigate methods to improve WMA and WMA-RAP mixtures performance
- study the applicability of semi-circular bending (SCB) test for 100 mm diameter samples using AC10 mix design. Moreover, the effect of notch lengths on the mechanical properties of SCB test results was also investigated.

1.3 Thesis organisation

There are five chapters in this thesis. Chapter 1 introduces the current problems and the objectives of the thesis. Chapter 2 reviews past studies and approaches of warm mix asphalt technologies. Chapter 3 describes material, mixtures preparation, and laboratory tests, including the binder's viscosity test, and mechanical characterisation tests such as moisture resistance tests, fatigue cracking, rutting resistance tests, indirect tensile tests, and semi-circular bending tests. Chapter 4 presents results from the tests mentioned in Chapter 3. Chapter 5 discuses results and gives conclusions as well as recommendations.

CHAPTER 2: LITERATURE REVIEW

2.1 Warm mix asphalt technology

Warm mix asphalt (WMA) is an emerging technology that has become an interesting and important topic among researchers and practitioners, since the technology promises to bring numerous benefits to society. Especially in the period when global warming and climate change are becoming worldwide issues, the use of WMA has become a priority. Besides the benefits that WMA can bring such as saving fuel, reducing gases during production, and extending the paving season, it is believed that WMA will last longer than HMA pavements (D'Angelo et al., 2008). Although there have been many studies conducted in laboratories (Hill et al., 2012; Lee et al., 2009; Topal et al., 2014) to investigate the behaviour of WMA, the use of WMA is still at trial levels and is still under observation (D'Angelo et al., 2008). The main aim of WMA technologies is to reduce production temperatures while still providing a comparable or better performance than HMA. WMA technologies can be classified into three categories, including the foaming process, using organic additives, and using chemical additives.

2.1.1 Foamed technologies

Foaming technologies aim to reduce the viscosity of bitumen binder to improve coating and workability of the asphalt at low mixing and compaction temperatures. The mechanism of these technologies is to introduce a small amount of water into the hot binder. The binder expands in volume due to water evaporation and encapsulation in the bitumen, lowering binder viscosity and allowing better coating and workability (Bonaquist, 2011; Van de Ven et al., 2007).

There are various foaming technologies, but they can be divided into two groups: water-based and water-containing (Zaumanis, 2010). In water-based technologies, water is injected directly into hot bitumen. In the second case, zeolites containing water in their structures are blended with hot bitumen and at high temperature (above 85°C), the water is released to foam the binder (Bonaquist, 2011; Capitão et al., 2012).

In the United States, there are several projects using commercial synthetic zeolites such as Aspha-min and Advera (Bonaquist, 2011). Most of the water-based technologies can lower the production temperature by 20-30°C compared with HMA, while using zeolite can reduce it by around 30°C (Kim et al., 2012).

2.1.2 Organic additives

In the early development of WMA in Europe, additives based on waxes or foamed technologies were introduced (Bonaquist, 2011). Waxes have low melting points and therefore they lower HMA production temperature to around 100°C (Bonaquist, 2011; Capitão et al., 2012; Silva et al., 2010a). At higher temperatures, waxes reduce the viscosity of the binder (Bonaquist, 2011), to compensate for the lower mixing temperature compared with HMA. At the cooling phase, the binder stiffness increases due to the crystallisation of waxes that form a lattice structure of microscopic particles (Bonaquist, 2011; Capitão et al., 2012); this improves the rutting resistance of the mixture (Jamshidi et al., 2013). Moreover, waxes are also believed to improve the lubrication of the binder, which results in improving mix workability at lower temperatures (Hanz et al., 2010), increasing the compactability of the mix.

There have been a number of additives introduced in the industry such as Sasobit®, Asphaltan-B, and Thiopave™ , and among them, Sasobit® is the most commercial product

(Capitão et al., 2012). Using organic additives can reduce mixing and compaction temperatures by up to 20-30°C (Zaumanis, 2010).

2.1.3 Chemical additives

Different types of chemical additives have been used in the United States and Europe in the last decade, amongst which Evotherm, being used from 2005 and Residet, being used from 2007 (Bonaquist, 2011), and Cecabase® RT are popular products. Although information on the chemical components of these products is not disclosed, they are reported to have surfactants, emulsification agents, aggregate coating enhancers and antistripping agents to improve the coating, stripping and adhesion at lower production and compaction temperatures (Bonaquist, 2011; Capitão et al., 2012). A reduction of roughly 30°C can be achieved for mixing and compaction by using chemical additives (Silva et al., 2010b).

2.1.3.1 Evotherm

In this research, there were two types of additives used. They are Evotherm 3G and Sylvaroad™ RP1000, and both belong to this chemical additive category. Evotherm is a well-known WMA additive that has been used in many studies (Leng et al., 2013; Zhang, 2010). Initially, the product was named Evotherm™, and was a package of emulsification agents. During mixing, the water within the emulsion evaporated and enhanced the aggregate coating. Evotherm 3G is the latest, third-generation product, and uses water-free technology. The product was released in 2008 by MeadWestvaco and its partner corporations Paragon Technical Services and Mathy Technology & Engineering (Kuang, 2012). The additive is added to the heated binder before the mixing process. Past literature reviews show that WMA using Evotherm 3G showed quite similar rutting performance and fracture resistance to conventional hot mix asphalt concrete, although it had slightly lower tensile strengths and dynamic moduli than the control mix (Leng et al., 2013).

2.1.3.2 Sylvaroad

In 2013, the Arizona Chemical Company released a WMA technology product called Sylvaroad^{TM} RP1000. This product is made from Crude Tall Oil and Crude Sulphate Turpentine, pine chemicals produced by the pulp and paper industry (Smith, 2015). The product was developed to increase the ability to add a higher proportion of RAP while still maintaining the good performance of warm mixtures (Arizona-Chemical, 2013). So far, there have been limited published research articles about this new product, although information can be found on unpublished media such as the company's website. As the new product is quite promising, the investigation of Sylvaroad as a potential warm mix additive is meaningful in terms of enhancing the possibility of incorporating high RAP content in WMA.

2.2 Reclaimed asphalt pavement

Reclaimed asphalt pavement (RAP) is a product of old pavement. RAP contains aggregate and binder, the latter of which becomes very hard after long-term ageing. Re-using RAP not only utilises the old material, but also saves the costs of dumping and processing the waste of old pavement. Every year, the construction of new roads requires a huge amount of asphalt concrete. According to the available data, in 2007 alone, the world produced about 1.6 trillion metric tons of asphalt (EAPA/NAPA, 2011). The production of fresh asphalt concrete requires a huge amount of non-renewable materials. With the continuous use of non-renewable materials without any replacement, a shortage of materials will be inevitable. For sustainable development, the use of RAP is vital and necessary.

2.3 The integration of WMA and RAP

Warm mix asphalt is a very promising technology. However, the technology is still under observation and needs to be improved as the long-term performance of WMA is still unknown (Capitão et al., 2012). The warm mix asphalt technology would have a severe setback if the new technology made the pavement fail sooner than the HMA. This would also have an adverse influence in terms of protecting the environment, as rebuilding means more excavating, mixing and compacting, which release dust and gases that contaminate the environment.

The use of RAP has been considered by researchers and practitioners, as using RAP can obviously bring many benefits. Adding RAP in warm mix asphalt technology increases the sustainability of the technology. The idea of using RAP in WMA is not only because RAP can enhance the sustainability of the technology, but also because RAP can improve the stiffness of the WMA and therefore improve the rutting resistance.

2.4 Mechanical evaluation of WMA and WMA-RAP mixtures

In recent years, there have been numerous studies carried out to investigate the performance of WMA and WMA incorporating Reclaimed Asphalt Pavements (RAP). This investigation covers the mechanical performance evaluation of different WMA and WMA-RAP mixtures with different additives and RAP contents. The main performance evaluations investigated by researchers include moisture resistance, fatigue cracking, low-temperature cracking, and rutting resistance. This part presents the literature reviews for evaluations covered in this project, including moisture susceptibility, fatigue cracking, and rutting resistance.

2.4.1 Moisture sensitivity

In service life, asphalt pavement is exposed to moisture from the surrounding environment. Over time, moisture intrudes into asphalt concrete, causing bond loss between binder and aggregates or between binder and fillers. These phenomena result in degradation of the mechanical performance of asphalt mixtures, known as moisture sensitivity or moisture damage. The continuous degradation and stripping of the asphalt mix can lead to potholes and raveling as shown in Figure 2.1.

Figure 2.1 Moisture damage in asphalt pavement

Warm mix additives were developed to reduce the viscosity of the binder, allowing mixing and compacting at lower temperatures than for HMA. At lower production temperatures, aggregate may not be completely dry, which prevents binder and aggregate from good adhesion, leading to moisture damage of asphalt mixtures (Mogawer et al., 2009; Xiao et al., 2010). The moisture resistance performance of WMA is much dependent on the additive used, as some additives not only reduce the viscosity of binder but also contain antistripping agents.

The addition of RAP into WMA mixtures may be a concern in terms of the moisture resistance, as RAP may not be completely dry, or the binder in RAP may not mobilize enough, leading to partial coating of aggregate (Zhao et al., 2015). Some researchers investigated the moisture resistance of WMA utilising RAP and concluded that incorporating a high RAP content will enhance or satisfy the moisture resistance of mixes (Dinis-Almeida et al., 2012; Hill et al., 2013; Rogers, 2011; Shu et al., 2012). However, others reached the opposite conclusion and were still concerned about moisture susceptibility of WMA incorporating high RAP content (Guo et al., 2014; Nejad et al., 2014; Tao and Mallick, 2009).

Moisture sensitivity is normally measured by using the tensile strength ratio, where mixes in dry and wet conditions are tested to calculate the ratio of tensile strength in these two situations. Indirect tensile strength test, shown in Figure 2.2, is a commonly used test in laboratories due to its simplicity. The test can be carried out on 100 ± 2 mm diameter specimens with a thickness of 65 ± 1 mm, or on 150 ± 2 mm diameter specimens with a thickness of 85 ± 1 mm (AG:PT/T232, 2007).

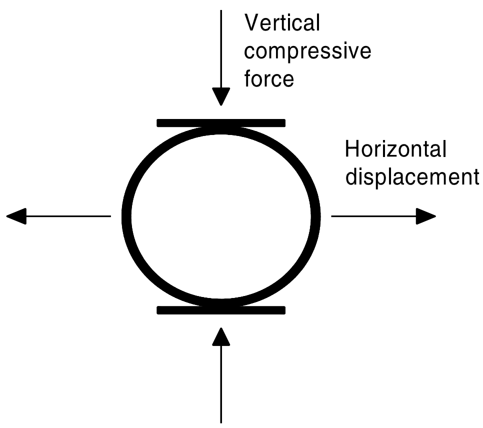

Figure 2.2 Indirect tensile strength test

The indirect tensile strength is calculated as per Equation 2.1:

$$ITS = \frac{2P}{\pi \times t \times D} \qquad \textbf{(2.1)}$$

where:

ITS = indirect tensile strength (MPa)

P = peak compressive force (N)

t = specimen thickness (mm)

D = specimen diameter (mm)

The tensile strength ratio (TSR) is then calculated as shown in Equation 2.2:

$$TSR(\%) = \frac{ITS_{wet}}{ITS_{dry}} \qquad \textbf{(2.2)}$$

where:

ITS_{wet} = indirect tensile strength of specimen in wet condition

ITS_{dry} = indirect tensile strength of specimen in dry condition

2.4.2 Fatigue resistance

Fatigue cracking has been recognized as one of the major distresses in asphalt pavements. This phenomenon usually happens at intermediate temperatures. Fatigue cracking occurs due to repeated traffic loading, causing tensile stresses and strains in the bituminous layers. Under repeated stresses, microcracks occur. After several applications of traffic loads, microcracks develop and propagate through the pavement. Normally, cracks start at the bottom of bituminous layers then propagate upward to the top of the surface in bottom-up cracks, as shown in Figure 2.3. Top-down fatigue cracks are also common in thin asphalt pavements due to high tyre pressures.

Past literature shows that WMA performed similarly or slightly worse than HMA in fatigue tests (Sanchez-Alonso et al., 2013; Su et al., 2009; Yang et al., 2012), although theoretically WMA with less-aged binder is expected to withstand fatigue better than HMA with highly aged binder during mixing, storing and paving. In terms of WMA incorporating RAP, past literature reviews show that high RAP content will make asphalt mixtures stiffer and more brittle (Sengoz and Oylumluoglu, 2013), which results in decreasing fatigue life (Guo et al., 2014; Rogers, 2011) and low-temperature cracking resistance (Guo et al., 2014; Lee et al., 2009; Tao and Mallick, 2009; You et al., 2011). Nevertheless, in a study (Zhao et al., 2013) , in which the WMA contained 30% RAP, it was concluded that WMA-RAP mixture generally performed similarly or even better than HMA in terms of cracking and fatigue resistance, implying that cracking and fatigue might not be a concern for WMA-RAP mixtures. The authors also pointed out that there might be adverse effects with the introduction of more than 30% RAP into WMA (Zhao et al., 2013); therefore, an RAP content of 30% was considered the maximum in WMA-RAP mixtures. In another study (Nejad et al., 2014), Nejad recommended that the addition of RAP in the mixes should not exceed 50%.

In the laboratory there are numerous testing methods used to evaluate fatigue performance of asphalt mixtures, such as the bending beam fatigue test, the push-pull fatigue test and the indirect tensile fatigue test. Of these, the bending beam fatigue test is a very common choice, and is used widely.

Figure 2.3 Pavement fatigue cracking

2.4.3 Rutting resistance

Rutting or permanent deformation is one of the major distresses in flexible asphalt pavements, and happens at high temperatures under traffic loading. Rutting is the depression in the wheel path on the road surface. Each time a traffic load is applied, a small permanent deformation occurs in the pavement. Micro rut depths accumulate to high rut depth and this causes rutting distress.

There have been many laboratory studies showing that WMA generally has lower rutting resistance than HMA (Mo et al., 2012; Zhao et al., 2012). At lower production temperatures, the binder in WMA is less aged, becoming softer than HMA, and this is believed to reduce the rutting resistance of WMA (Zhao et al., 2012). Trial sections, paved with WMA and HMA for comparison, showed that after the duration of two years, WMA performed similarly to HMA in rutting resistance (Zhang, 2010). However, the period of two years is still too short compared to the whole service life of asphalt pavement to conclude that WMA would perform as well as HMA in terms of rutting resistance.

There have been numerous studies showing that the inclusion of RAP in WMA improves the rutting resistance of mixtures, and that the rutting resistance increases as more RAP is added into the WMA due to the high stiffness of the aged binder in RAP (Hill et al., 2013; Lee et al., 2009; Mallick et al., 2008; Nejad et al., 2014; Rogers, 2011; Shu et al., 2012; Zhao et al., 2013). However, rutting resistance of WMA-RAP may still be a concern as it showed higher rut depth than HMA in a study by Zhao and his co-authors (Zhao et al., 2013).

In the laboratory, rutting behaviour of asphalt mixtures can be evaluated by using dynamic modulus, dynamic creep or wheel tracking tests.

2.4.3.1 Dynamic modulus test

The dynamic modulus test, also called complex modulus test, is carried out by applying a repeated uniaxial, sinusoidal loading at various frequencies and temperatures and measuring the recoverable strain and deformation of the asphalt specimens. This type of test can be used to evaluate the viscoelastic properties of specimens by measuring the phase angle, defined as the lag between peak stress and peak strain, as shown in Figure 2.4. The test provides insight into permanent deformation resistance of pavement in service.

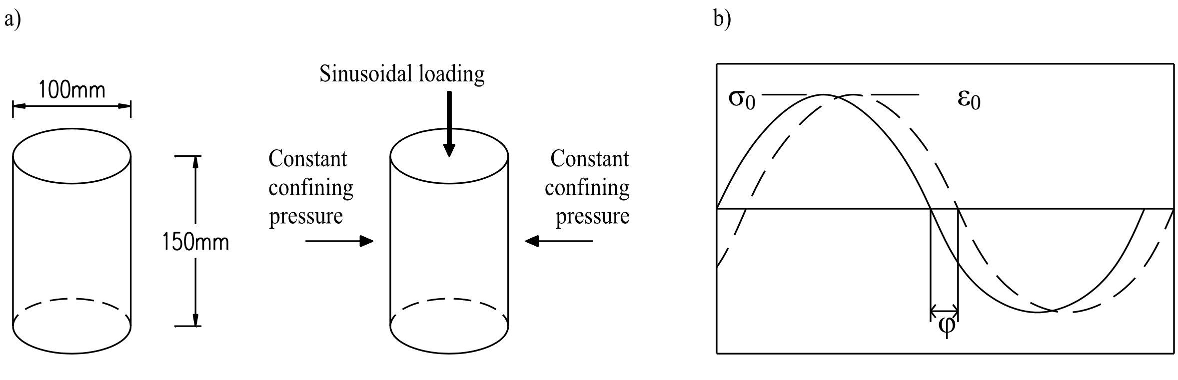

Figure 2.4 (a) Specimen and (b) parameters determined in complex modulus test

In the dynamic modulus test, there are two parts measured: one is the elastic component and the other is the viscous component. The elastic component helps pavement to recover under loading and the viscous component causes permanent deformation. The following equation exhibits the components of the complex modulus (Witzcak, 2002):

$$E^* = \left|E^*\right| \cos\varphi + i\left|E^*\right| \sin\varphi \qquad \textbf{(2-3)}$$

where:

E^*= complex modulus

$|E^*|$= dynamic modulus

φ= phase angle. If φ=0, the mix is pure elastic, while if φ=90, the mix is pure viscous.

i= imaginary number

Dynamic modulus is calculated as per Equation 2.4:

$$\left|E^*\right| = \frac{\sigma_0}{\varepsilon_0} \qquad \textbf{(2.4)}$$

where:

σ_0 = maximum stress

ε_0= maximum strain

2.4.3.2 Dynamic creep test

Dynamic creep test is a simple test used to investigate the rutting resistance of asphalt mixtures. There are two testing modes: confined and unconfined mode. Samples used for this test have the same dimensions as those used for the dynamic modulus test, or samples from the dynamic modulus test can be utilised as the dynamic modulus test is non-destructive.

However, the operator must check carefully for any signs of damage, because minimal damage may occur during the dynamic modulus test, according to the research of Elseifi and co-authors (Elseifi et al., 2014). During the test, the sample is subjected to a repeated haversine axial compressive load pulse of 0.1 second every 1 second. For the confined mode, the constant confining pressure is applied during the test. For the unconfined mode, only axial compressive load is applied. During the test, the permanent axial strains and the number of load cycles were recorded and plotted for analysis, as shown in Figure 2.5.

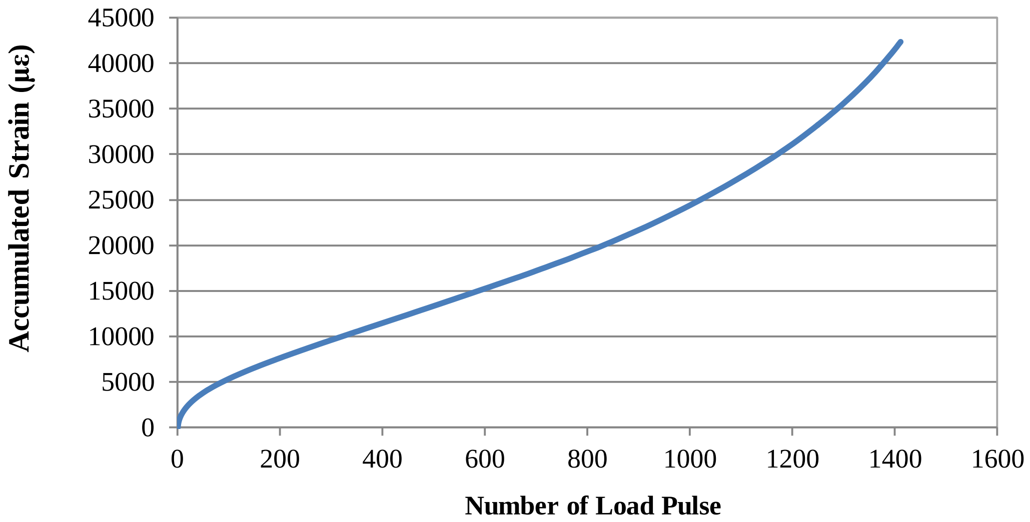

Figure 2.5 A typical test result of the dynamic creep test

2.4.3.3 Wheel tracking test

Besides the dynamic modulus and dynamic creep tests, a wheel tracking test is also commonly used to evaluate rutting performance of asphalt mixtures. The advantage of the test is that it can simulate the interaction between the loaded wheel and asphalt concrete, and the test result is expected to closely reflect the rutting performance of pavements in service. However, the test also has disadvantages compared to the dynamic modulus or dynamic creep test, such as the test being time-consuming and requiring larger amounts of material for making samples.

There are several types of wheel tracking test equipment, such as the Hamburg Wheel Tracking Device (HWTD), Asphalt Pavement Analyzer (APA) and French Wheel Tracker (See Figure 2.6). The mechanism of these tests is to simulate the effect of traffic on pavement in service. When a specimen is prepared, it is placed into the test apparatus and conditioned to the desired temperature before testing. In the testing phase, a loaded wheel runs back and forth on the prepared specimen. The number of cycles and the rut depth are recorded throughout the test. These values can be plotted to evaluate the rutting resistance of asphalt mixtures.

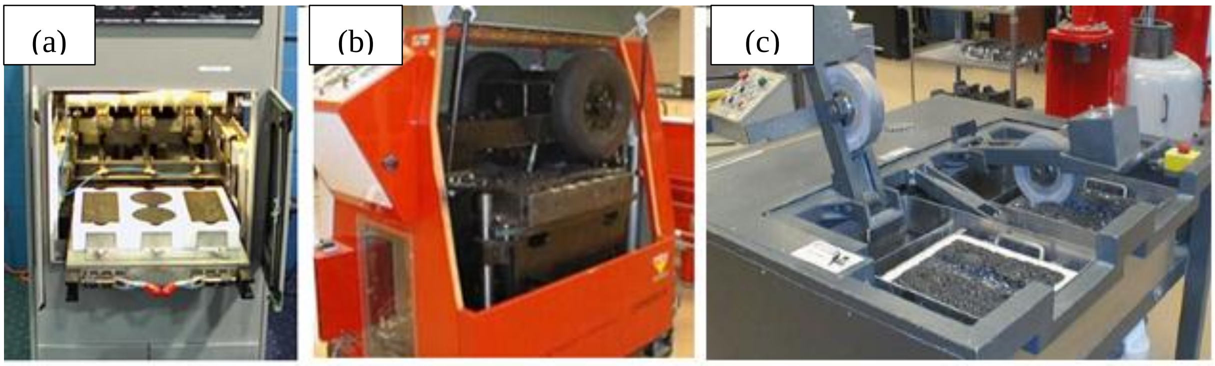

Figure 2.6 (a) Asphalt Pavement Analyzer; (b) French Wheel Tracker (Pavementinteractive, 2011), (c) Hamburg Wheel Tracking Device (Stuart and Youtcheff, 2001)

2.4.4 Semi-circular bending test

As previously discussed, fatigue cracking is mainly caused by the repeated tensile stresses and strains caused by the traffic loading (Artamendi and Khalid, 2006; Huang et al., 2013), or by the change of temperature in pavements, building up the thermal stresses and causing cracking (Artamendi and Khalid, 2006; Li and Marasteanu, 2010). Cracking failure includes two phases: cracking initiation and cracking propagation (Huang et al., 2013). Because cracking failures greatly affect the ride quality and long-term performance of the pavement, an in-depth understanding of the cracking mechanism is vital for pavement design (Lancaster et al., 2013). However, asphalt mixtures are complex materials; their behaviors are combinations of viscous and elastic characteristics. Thus, their performance is greatly dependent on loading rates and temperatures , which makes the analysis of cracking more complicated (Lancaster et al., 2013).

Cracking in pavements is strongly related to the tensile strength of asphalt mixtures (Huang et al., 2005). Thus, many researchers have tried to determine the tensile strength of asphalt by using test methods such as the indirect tensile test (IDT), the three or four points bending test, or the disk-shaped compact tension test (DCT) (Lancaster et al., 2013). Among these test methods, IDT has been widely used to measure the tensile strength of hot mix asphalt mixtures (Arabani and Ferdowsi, 2009; Huang et al., 2005) due to its simplicity, and also because samples can be easily cored from existing pavements, or fabricated in laboratories. Although the IDT test is easy to implement, the test has some disadvantages, such as the permanent deformation that is witnessed under loading strips, and the stress state during the test is quite complicated and not a realistic reflection of the actual performance in pavements (Arabani and Ferdowsi, 2009; Huang et al., 2005). In addition, the repeatability of the test is quite poor and a large coefficient of variation may be encountered (Arabani and Ferdowsi, 2009).

In recent years, the SCB test has been developed and widely used. The test was originally developed for determining the fracture resistance in rock mechanics (Huang et al., 2013), and has been successfully used to analyse the fracture properties of asphalt mixtures (Molenaar et al., 2002).The SCB test is gradually gaining more attention from researchers and engineers due to its simplicity, repeatability and consistency in investigating cracking characteristics of asphalt mixtures (Saha and Biligiri, 2015). There have been numerous studies of the SCB test (Abdo et al., 2012; Arabani and Ferdowsi, 2009; Artamendi and Khalid, 2006; Barman et al., 2014; Biligiri et al., 2012; Cao et al., 2009; Elseifi et al., 2012; Huang et al., 2005; Huang et al., 2013; Lancaster et al., 2013; Lancaster and Khalid, 2014; Li and Marasteanu, 2010; Li et al., 2010; Liu, 2011; Mahmoud et al., 2014; Molenaar et al., 2002; Nsengiyumva, 2015; Pérez-Jiménez et al., 2013; Saha and Biligiri, 2015; Teshale, 2012; Teshale et al., 2013; Wang et al., 2013; Zegeye et al., 2012). Of these, only one study (Arabani and Ferdowsi, 2009) used SCB samples with 100 mm diameter to compare with the IDT and Hveem tests. The authors concluded that results from the three tests were convertible. This indicates that samples with 100 mm diameter are applicable. However, in the two current available testing standards for the SCB test, EN 12697-44:2010 (EN12697-44:2010), released in 2010, and AASHTO TP 105-13 (AASHTO-TP-105-13, 2013) released in 2013, only 150 mm diameter samples are referred. For the IDT test, 100 mm diameter samples can be used for asphalt mixtures with nominal aggregate size of 10 mm and 14 mm, as in New Zealand and Australian standards. The question is whether 100 mm diameter samples are applicable for the SCB test. So far, there has been no thorough investigation to decide whether 100 mm diameter is applicable for SCB samples, and why. Moreover, the effect of notch length on the mechanical characteristics of the SCB test for 100 mm diameter samples also needs to be investigated to produce information on suitable notch lengths for the SCB test using 100 mm diameter samples. The set-up for the SCB test can be seen as in Figure 2.7.

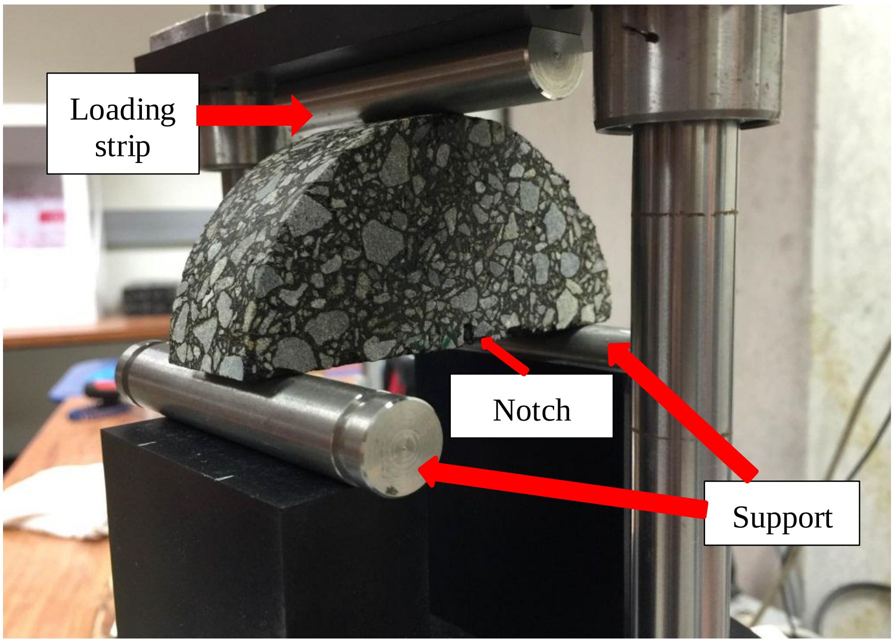

Figure 2.7 Apparatus for SCB test

2.5 Summary

It can be seen that the literature reviews still show inconsistent conclusions from previous studies. Thus, further investigation about the performance of WMA-RAP mixtures is necessary to check the possibility of incorporating high RAP content into WMA by investigating WMA-RAP performances. Moreover, the new additive Sylvaroad is a relatively new rejuvenator with very limited research as a potential WMA additive; thus, an investigation of the new additive as a future candidate for WMA technology incorporating high RAP content is necessary. The study is also important in terms of investigating the reasons that prevent the addition of high RAP content into WMA. From the study, solutions will be recommended to improve the WMA-RAP performance.

This study will also investigate the SCB test, a relatively simple test, but very promising in giving important information about a mixture's characteristics, such as tensile strength and fracture properties. The simplicity of the SCB test and its ability to give informative results, makes it both interesting and important, and suggest further study is necessary.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

This chapter presents the research methodology of this study. Materials preparation, mix design, binder characterisation tests, and mixture performance tests are described.

To start the experimental study, materials preparation was firstly carried out. The materials preparation part consists of securing reclaimed asphalt pavement (RAP), warm mix additives, virgin aggregate, and binder. The preparation part also comprises determining RAP’s properties, including RAP’s binder content, grading for extracted aggregate, specific gravities, and absorption.

The next part covers the mixtures design, which includes designing aggregate gradation, choosing mixing and compaction temperatures, and determining the optimum binder contents for each mix type.

The research covers the viscosity test of the unaged and long term aged binder for the modified and unmodified binders. The final part is the mechanical performance tests, which cover the study of moisture resistance of mixtures, fatigue cracking, rutting resistance, and semi-circular bending (SCB) test. The research plan for this study is summarised in the flowchart shown in Figure 3.1 below.

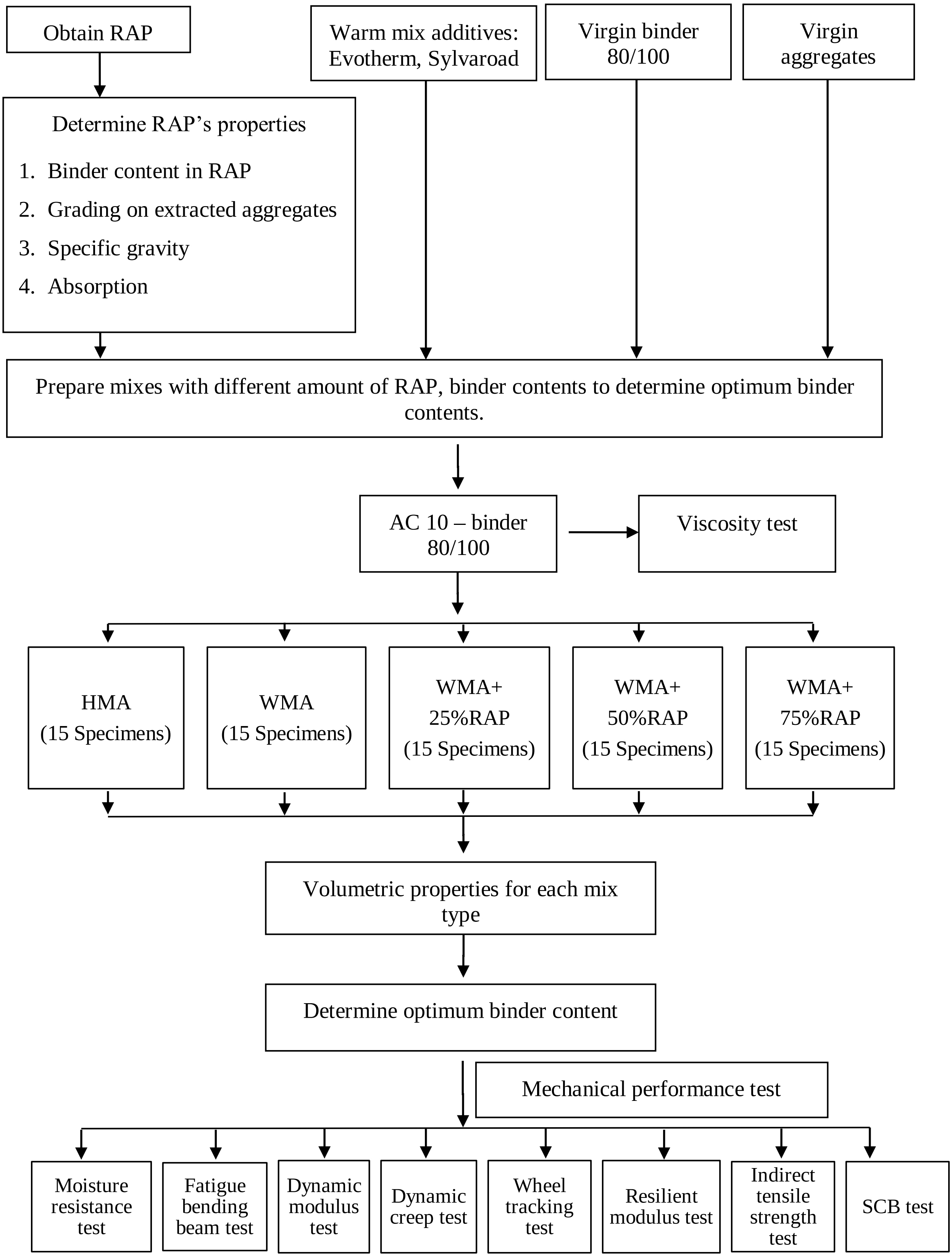

Figure 3.1 Research schematic of the project

3.2 Material preparation

New Zealand standard AC 10 dense graded asphalt mix was used in this research. The AC 10 is a dense graded mix with a maximum nominal aggregate size of 10 mm. Bitumen used in this research was 80/100 penetration grade. The AC10 dense graded mix made of 80/100 penetration grade bitumen is usually used in New Zealand as a wearing course surface layer for moderately trafficked roads. AC10 in this research was designed for heavy traffic roads. This research used two types of additives, namely, Evotherm 3G and Sylvaroad^{TP} RP1000.

3.2.1 Virgin aggregates

Virgin aggregates were secured from one of the local contractors in Christchurch. Aggregates used for this research were collected from four classified categories: SC10, concrete sand, HP and BARMAC. To ensure the homogeneity of material used, aggregates were collected from the same stockpiles and stored in 20-litre containers. The amount of aggregate was calculated carefully to make sure that there was enough for the whole study, to avoid recollecting from other stockpiles. Aggregate pails were then transported to the Transportation Laboratory at the University of Canterbury to make test specimens. Information about the properties of each type of aggregate is shown in Table 3-1.

Table 3-1 Aggregate properties

Aggregate	SC10	Concrete Sand	BARMAC	HP
Sieve Size (mm)				
13.2	100	100	100	100
9.5	99	100	100	100
6.7	31	100	100	100
4.75	0	99	98	99
2.36	0	77	59	67
1.18	0	64	40	45
0.6	0	56	29	32
0.3	0	34	21	23
0.15	0	7	14	16
0.075	0	1	9	10
Bulk SG	2.65	2.63	2.62	2.62
Bulk SG SSD	2.67	2.65	2.65	2.65
Apparent SG	2.7	2.68	2.69	2.69
Absorption (%)	0.8	0.7	0.9	1

3.2.2 Bitumen

Bitumen 80/100 penetration grade was used in this research. Bitumen was collected and contained in small containers to avoid multiple heatings before sending it to the Transportation Laboratory, University of Canterbury.

3.2.3 Evotherm 3G

Evotherm 3G is a liquid additive that is commonly used for warm mix asphalt production. It is commercially available as PC-1770 in New Zealand. Evotherm was provided by Brenntag New Zealand Limited. According to the supplier, Evotherm is able to reduce the viscosity of mixtures at high temperatures, allowing 30–50°C reduction in mixing and compacting temperatures.

3.2.4 Sylvaroad^{TP} RP1000

Sylvaroad^{TP} RP1000 is a rejuvenator and it is a relatively new product, released in 2013 in the USA. Sylvaroad was provided by Arizona Chemical Limited. Similar to Evotherm, Sylvaroad is introduced to reduce the viscosity of the binder, rejuvenate the binder in RAP and enhance the ability of the addition of large amounts of RAP in WMA. This additive is also in liquid form. Both Evotherm and Sylvaroad were stored in glass bottles to avoid chemical interaction between the containers and the additives. The two additives can be easily recognized as their colours are relatively different (Figure 3.2): Evotherm looks dark yellow and Sylvaroad looks green and clear.

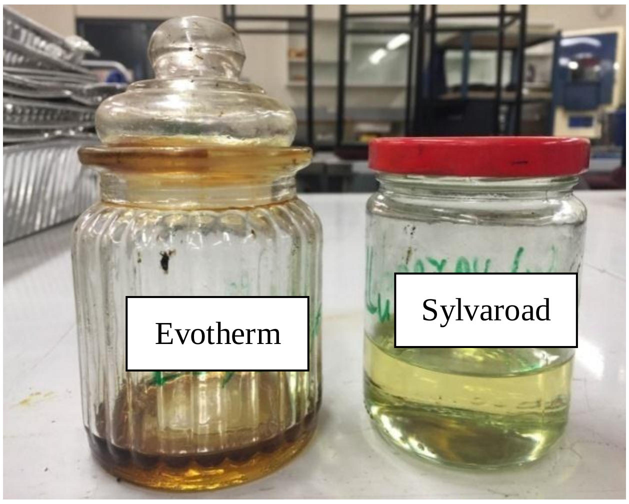

Figure 3.2 Evotherm (left) and Sylvaroad (right) additives

3.2.5 Reclaimed asphalt pavement (RAP)

The reclaimed asphalt pavement RAP constituted 12-years-old pavements and it was collected in a stockpile from the same contractor. Similarly to aggregates, they were collected from a stockpile and contained in 20 litre pails, and used for the whole project to ensure the homogeneity of the material.

RAP was extracted to determine the binder content and to investigate the aggregate gradation, see Figure 3.3. Extracted aggregate was tested at the Transportation Laboratory, Canterbury University, to determine the bulk specific gravities and absorptions, as shown in Table 3-2.

Figure 3.3 Reclaimed asphalt pavement after drying

Table 3-2 Basic properties of RAP

Sieve Size (mm)	Extracted aggregate gradation of RAP	New Zealand specification for AC10 (NZTA, 2014)	RAP properties
13.2	100	100	Bitumen content in RAP (%) 4.8 Extracted aggregate bulk specific gravity 2.607 Absorption= 0.96%
9.5	98	90-100	
6.7	83.3	68-82	
4.75	68.3	50-70	
2.36	49.3	32-51	
1.18	36.9	22-40	
0.6	30.2	15-30	
0.3	23.3	10-22	
0.15	15	6-14	
0.075	9.7	4-7	

3.3 Mix design method

There were five mixtures designed in this study, comprising HMA, WMA and WMA with 25%, 50% and 70% of RAP. New Zealand standard AC 10 dense graded asphalt mix was used in this research. The AC 10 is a dense graded mix with a maximum nominal aggregate size of 10 mm. For HMA, the mixing and compacting temperatures were the same, at 142°C, according to the AS/NZS 2891.2.1:2014 (AS/NZS, 2014a) and AS/NZS 2891.2.2:2014 (AS/NZS, 2014b). The WMA and WMA-RAP mixtures were mixed and compacted at 115°C and 110°C respectively, for both Evotherm and Sylvaroad. The WMA aggregate gradation was kept the same as the HMA. The WMA-RAP aggregate gradations were almost the same as HMA and WMA, as shown in Figure 3.4.

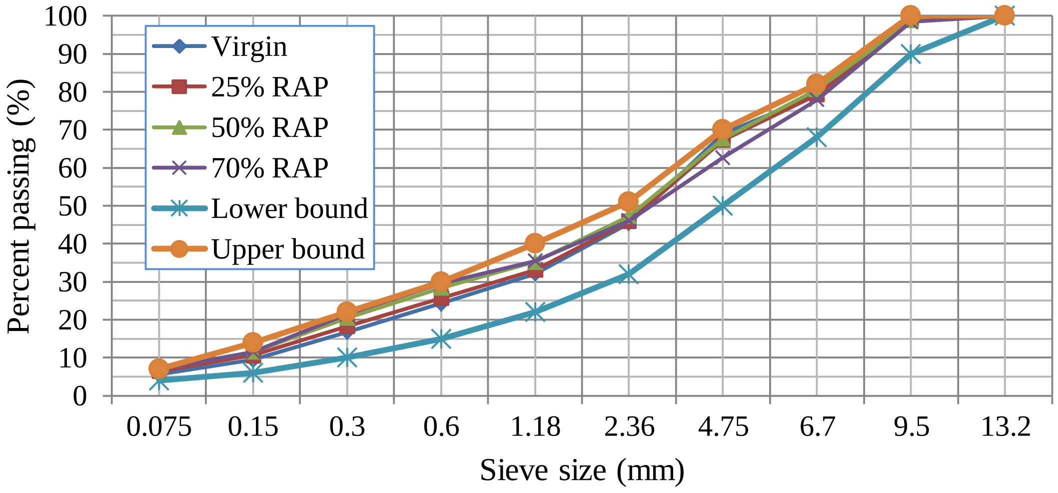

Figure 3.4 Gradation curves of mixes

The gyratory compactor shown in Figure 3.5 was used to compact the asphalt mix specimens in this study. All asphalt mix specimens for the mix design purpose were prepared with a height of 85 mm and a diameter of 150 mm. According to the AS/NZS 2891.2.2:2014 (AS/NZS, 2014b) standard, the ram pressure was 240 kPa, and the gyration angle was maintained at 3°. For New Zealand and Australian standards, the ram pressure of 240 kPa is much less than the 600 kPa recommended by Superpave. However, the angle of gyration for New Zealand and Australian standards is 3°, which is much larger than the angle of gyration (1.25°) recommended by Superpave. The larger angle of gyration compensates for the low ram pressure. The difference in compaction for different levels of traffic is the number of gyrations, which is specified in “Specification for dense graded and stone mastic asphalts – NZTA M10: 2014” (NZTA, 2014). In this research, the gyration number of 120 was chosen for heavy traffic.

Figure 3.5 Gyratory compactor

Optimum binder contents were chosen at the target air void of 4% as shown in Table 3-3 . In the case of WMA and WMA-RAP, optimum binder contents were firstly designed for mixtures with Evotherm. As this research primarily concentrates on the effect of additives on the mechanical performance of WMA and WMA-RAP mixtures, such as moisture susceptibility, rutting resistance or fatigue cracking, rather than the compatibility, the optimum binder contents for Evotherm mixtures were adopted for mixtures with Sylvaroad.

Table 3-3 Mix design properties

Mix type	**HMA**	**WMA**	**WMA+25%RAP**	**WMA+50%RAP**	**WMA+70%RAP**
V_a(%)	4	4	4	4	4
P_b(%)	5.1	4.8	4.6	4.3	4.2
VMA (%)	15.1	14.6	13.9	13.6	13.2
VFB(%)	73.5	72.5	71.1	70.6	69.7
G_{mm} (g/cm^3)	2.452	2.459	2.468	2.463	2.47

Where: V_a: air void content, P_b: optimum binder content by mass of the total mix, VMA: void in mineral aggregate, VFB: voids filled with bitumen, G_{mm}: maximum specific gravity

3.4 Experimental testing

The experimental testing programme consists of a binder test and mixture mechanical performance tests. In the first part, the binder test, the viscosity of the neat binder and long term aged binder was measured to study the consistency of the binder and the effect of additives on the binder's viscosity, for both modified and non-modified binders. The mechanical performance tests covered the study of moisture resistance of mixtures, fatigue cracking, rutting resistance, and the SCB test. The moisture resistance test was carried out to investigate the ability of mixtures to resist moisture damage by using the indirect tensile method. The fatigue cracking test was done to evaluate the fatigue cracking behaviour of asphalt mixtures under repeated loading, by using the bending beam fatigue test method. Dynamic modulus, dynamic creep, and wheel tracking tests were used to evaluate the rutting resistance of mixtures at high pavement temperatures. The SCB test was investigated to further study the cracking resistance of mixtures, and the possibility of using this test to indicate the tensile strength of the asphalt mixture instead of using the indirect tensile strength method. The repeatability and mechanical properties obtained from the SCB test were compared with the resilient modulus and indirect tensile strength tests. A summary of experimental test methods and specimens is shown in Table 3-4 below.

Table 3-4 Summary of experimental test methods

Test	Standard/Report	Purpose	Number of samples required / test
Binder tests	ASTM D4402/D4402M − 13 and ASTM D2872 – 12	Consistency	1
Moisture resistance	AG:PT/T232	Moisture damage	6
Fatigue	AG:PT/T233	Fatigue cracking	3
Dynamic modulus	NCHRP 614	Rutting	3
Dynamic creep	NCHRP 629	Rutting	3
Wheel tracking	AG:PT/T231	Rutting	2
Resilient modulus	AS 2891.13.1 - 1995	Support SCB study	3
ITS	ASTM D6931 – 12	Support SCB study	3
SCB	N/A	Cracking resistance	3

3.4.1 Binder test

The viscosity test aims to determine the viscosity of bitumen. The viscosity is an important characteristic as it shows the ability to pump the material during transportation and storing. Moreover, the viscosity also indicates the ability of bitumen to coat aggregate particles, fill the voids of aggregate during the mixing phase, and the compactability of asphalt mixture during construction. Viscosity is determined from the ratio between the applied shear stress and the induced shear rate of bitumen.

In this study, the viscosity test was carried out on the unaged and aged binder, with and without Evotherm and Sylvaroad, to evaluate the effect of the two additives on the binder's consistency. The testing procedure was in accordance to ASTM D4402M-13: "Standard Test Method for Viscosity Determination of Asphalt at Elevated Temperatures Using a Rotational Viscometer" (ASTM, 2013b). In the case of unaged binder, the additives were added directly into the heated virgin binder for testing. In the case of aged binder, the virgin binder was aged before adding the additives and testing.

During the production and compaction of asphalt concrete, the binder in asphalt is oxidized and aged. This phenomenon is called short-term ageing. In laboratory, short-term ageing of the binder is simulated by using the rolling thin film oven test, which can be carried out in accordance with ASTM D2872 – 12 "Standard test method for effect of heat and air on a moving film of bitumen (Rolling thin-film oven test)" (ASTM, 2013a). During the service life, the pavement is oxidized and aged; this is called long-term ageing. The long-term ageing of asphalt binder can be simulated by using the pressure aging vessel (PAV). In this study, the rolling thin film oven was used to simulate the long-term ageing of asphalt concrete. This method was used in a previous study by Alotaibi and Saleh (Alotaibi and Saleh, 2011). For this method, the ageing temperature was maintained at 125°C over a 24-hour period. The authors mainly aimed to age the binder to a certain level of ageing that is likely to occur in the field, to study the effect of additives on the aged binder's viscosity, rather than trying to achieve a similar ageing level of binder in the field.

Similarly to the unaged binder, the aged binder was also subjected to the viscosity tests with and without the additives. The viscosity tests were conducted at 100, 115, 130, 145 and 160°C. The tests were carried out from the lowest temperature to the highest temperature consecutively using a Brookfield rotational viscometer, shown in Figure 3.6.

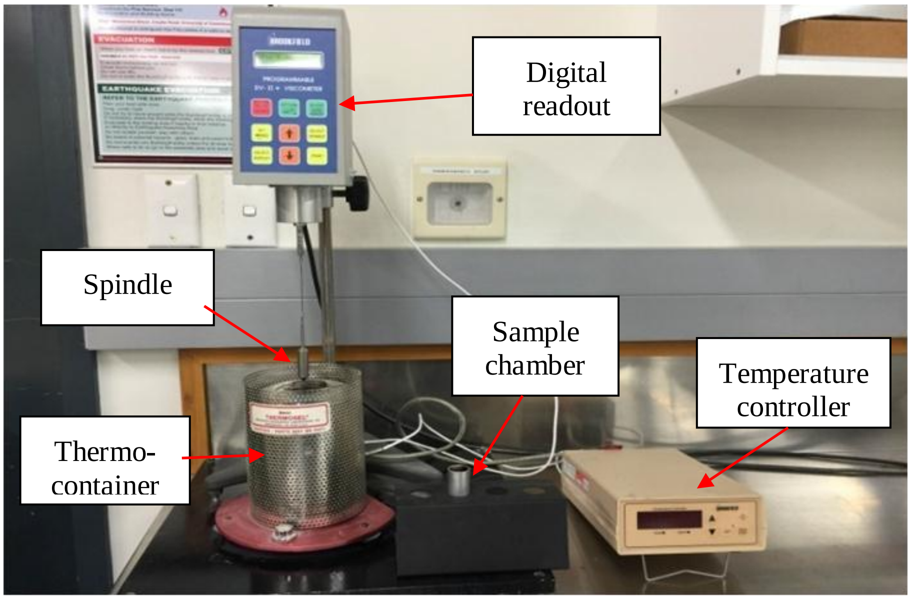

Figure 3.6 Apparatus for viscosity test

3.4.2 Indirect tensile test method

3.4.2.1 Moisture resistance test

The moisture sensitivity was investigated by using tensile strength ratio (TSR) according to the AG:PT/T232 (AG:PT/T232, 2007). Cylindrical specimens of 150 mm diameter and 85 mm height were prepared. The air void target for the test specimens is 8.0 ± 1.0%. For each mixture, six specimens were produced and divided into dry and wet subsets as shown in Figure 3.7a. The average air void of each subset was kept at 8.0% with a maximum difference between the two subsets of 0.5%. The dry subsets were conditioned in the oven at 25°C for two hours, and then the height was measured before being subjected to the ITS test. For the wet subsets, samples were firstly vacuum saturated to reach the saturation degree of 55–80% as shown in Figure 3.7b. They were then conditioned in water for 24 hours in a temperature-controlled water bath at 60°C, as shown in Figure 3.7c. After being removed, the samples were conditioned at 25°C for two hours before measuring the height and testing for ITS. The indirect tensile test shown in Figure 3.7d was carried out at 25°C and the displacement rate is

50 mm/minute. Tensile strength ratio (TSR) was calculated by dividing the average ITS of specimens in the wet condition by the average ITS of samples in the dry condition.

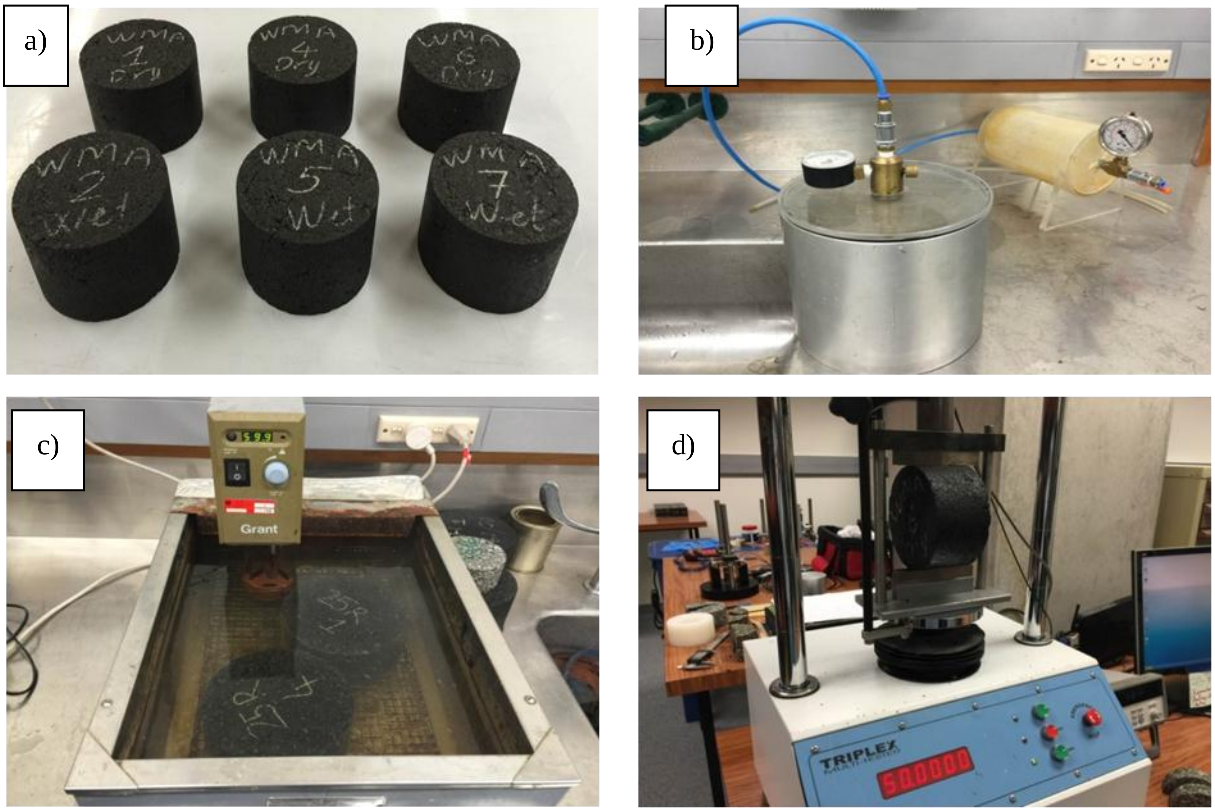

Figure 3.7 Sample preparation and testing for moisture resistance. (a) Preparation of 6 samples, 3 for wet condition testing and 3 for dry condition testing; (b) Pycnometer used in order to partially saturated samples; (c) Conditioning samples for wet condition testing; (d) Testing using indirect tensile test method

The tensile strength derived from the indirect tensile test was calculated as per Equation 3.1:

$$S_t = \frac{2 \times 1000 \times P}{\pi \times D \times h_c} \qquad \textbf{(3.1)}$$

where:

S_t= tensile strength, kPa; P= peak load, N

D= diameter of sample, mm; h_c= thickness of sample, mm

3.4.2.2 Indirect tensile strength test

The ITS test was conducted according to ASTM D6931 – 12 “Standard Test Method for Indirect Tensile (IDT) Strength of Bituminous Mixtures” (ASTM, 2012), see Figure 3.8. The samples used for this test were from the resilient modulus test (Part 3.4.7) as the indirect stiffness modulus test is a non-destructive test. Similarly to the moisture resistance test for the dry subset, the loading rate was 50 mm/minute and testing temperature was 25°C. Tensile strength was calculated by using Equation 3.1.

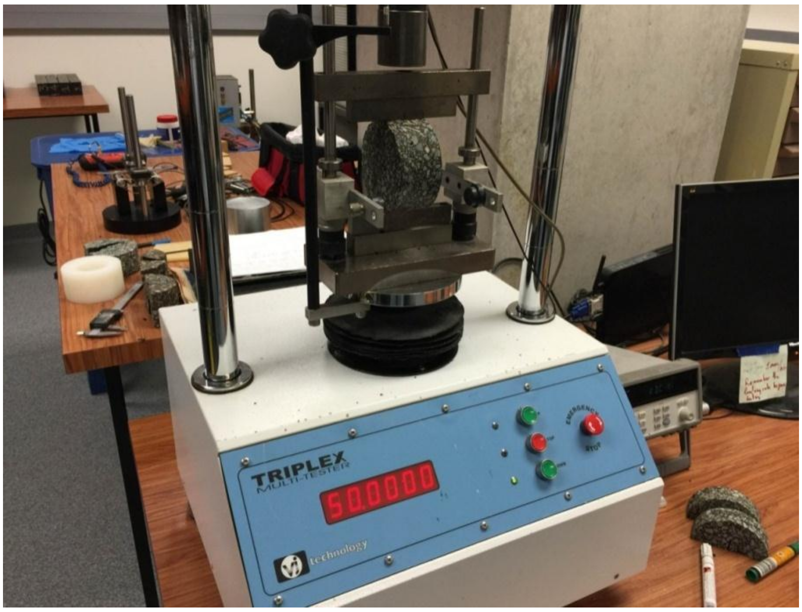

Figure 3.8 Testing set-up for indirect tensile strength

3.4.3 Bending beam fatigue test

The bending beam fatigue test was used to evaluate the fatigue cracking resistance of the asphalt mixes. Specimens were produced and tested according to the AG:PT/T233 “Fatigue life of compacted bituminous mixes subject to repeated flexural bending” (AG:PT/T233, 2006). Slabs, as shown in Figure 3.9a, with the dimension of 305 x 405 x 75 mm were produced for all mixtures. These slabs were then cut into beams with the dimension of 50 mm high, 65 mm wide and 405 mm long as shown in Figure 3.9b. All the test beams had the air voids in a range of 6.1–7.9%. For this research, the asphalt concrete beams were tested in the constant displacement/strain mode. All the samples were subjected to a sinusoidal load at 10 Hz and maximum strain amplitude of 400 microstrain. The samples were kept in a temperature chamber, as shown in Figure 3.9c, at 20°C for 2 hours before testing. The number of cycles to fatigue failure is determined as the number of cycles at which the stiffness of samples decreases to 50% of its initial stiffness.

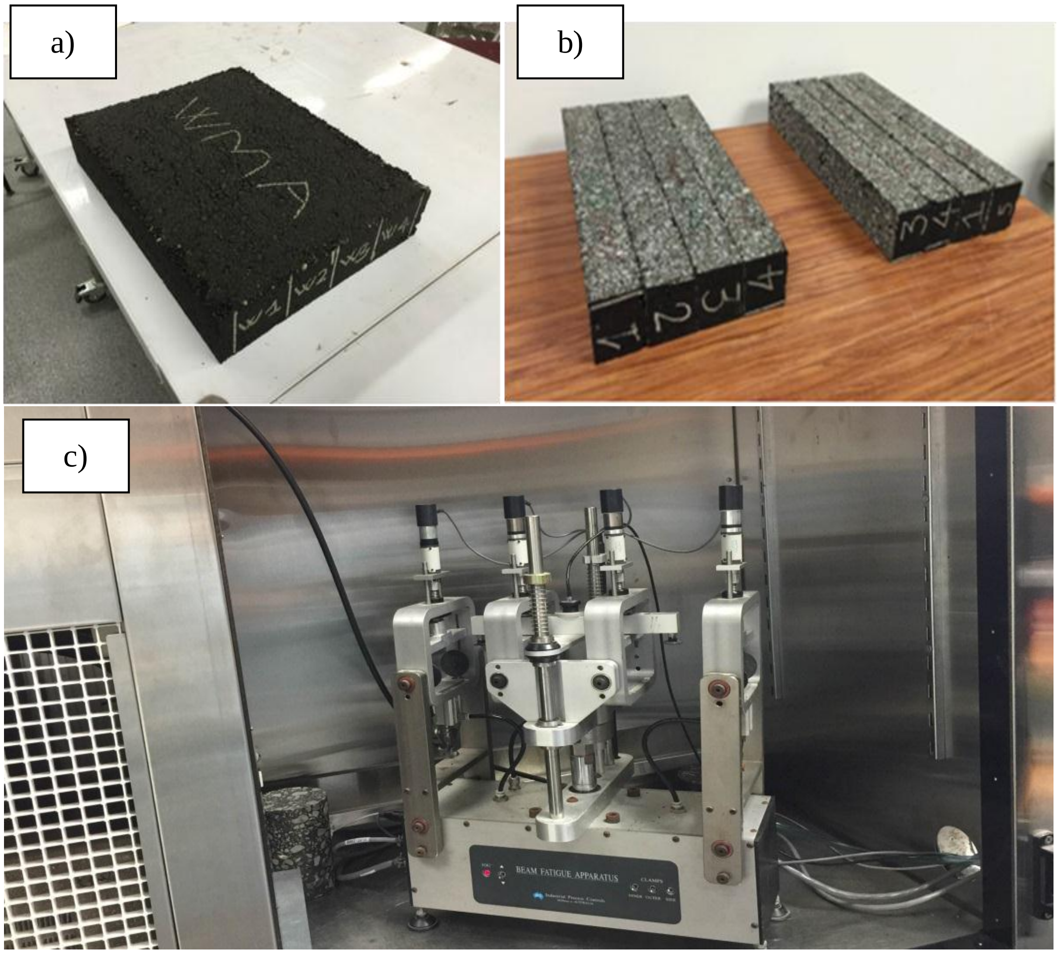

Figure 3.9 Sample preparation and testing apparatus for fatigue test. (a) Compacted slabs; (b) Beams for fatigue test cut from slabs; (c) Four-point bending beam in a temperature-controlled chamber for fatigue testing

3.4.4 Dynamic modulus test

The dynamic modulus ($|E^*|$) test is carried out by applying a repeated uniaxial loading at various frequencies and temperatures to measure the recoverable strain and deformation of specimens.

In this study, the dynamic modulus test was based on the NCHRP Report 614 "Refining the Simple Performance Tester for Use in Routine Practice" (Bonaquist, 2008a). Three replicates were prepared for each mixture. Cylindrical specimens of 150 mm diameter and 177 mm height were prepared by the gyratory compactor and then were cored and sawn into specimens with the dimensions of 100 mm in diameter and 150 mm in height, as shown in Figure 3.10a. All the test specimens had the air voids in a range of $5.0 \pm 1\%$. Three linear variable differential transducers (LVDTs) were attached on each specimen as shown in Figure 3.10b. The specimens were tested at four different temperatures, 4.4, 21.1, 37.8, 50°C, and five different frequencies, 10, 5, 1, 0.5 and 0.1 Hz. To avoid damaging the specimens during the test, they were tested from the lowest temperature to the highest temperature and from the highest frequency to the lowest frequency.

Results of the dynamic modulus test were used to develop master curves at a reference temperature. In this research, the reference temperature was 20°C.

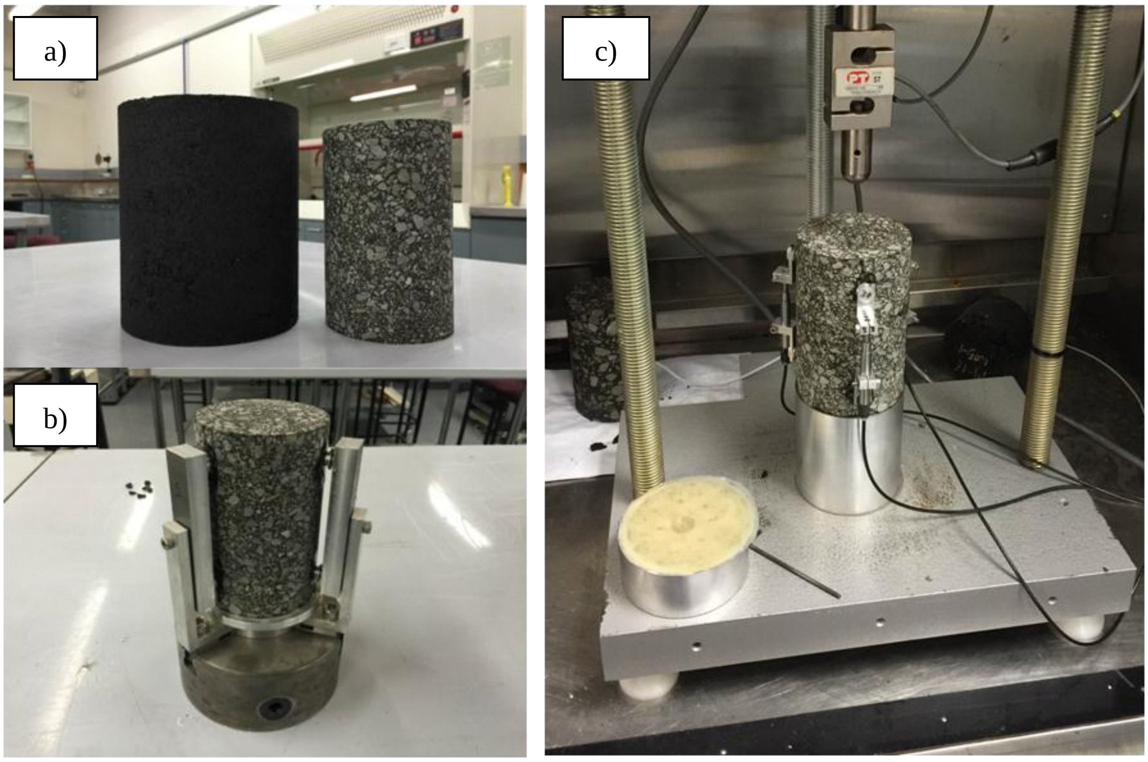

Figure 3.10 Sample preparation and testing apparatus for dynamic modulus test. (a) Sample before and after coring and cutting; (b) Gluing the mounting studs to install LVDTs; (c) Sample in position for testing.

3.4.5 Dynamic creep test

Dynamic creep test is a simple test used to investigate the rutting resistance of asphalt mixtures. In this study, the unconfined mode was selected to carry out the dynamic creep test as described in NCHRP Report 629 "Ruggedness Testing of the Dynamic Modulus and Flow Number Tests with the Simple Performance Tester" (Bonaquist, 2008b). Because the dynamic modulus test is a non-destructive test, the same specimens used in the dynamic modulus test were used in the dynamic creep test. After the dynamic modulus tests were finished at 50°C, the dynamic creep tests were conducted immediately at the same temperature. During the test, the samples were subjected to a repeated haversine axial compressive load pulse of 0.1 second every 1 second with a deviator stress of 140 kPa.

The permanent axial strains and the number of load cycles were recorded during the test. The test was terminated either when the axial strain reached 50,000 micro strains or the load cycles number reached 10,000. The testing apparatus for this test is the same one used for the dynamic modulus test (Figure 3.10c)

3.4.6 Wheel tracking test

In addition to the dynamic creep test, the wheel-tracking test was carried out to evaluate the rutting resistance of all asphalt mixtures used in this research. The test was conducted using a modified test set-up. Slab samples were prepared with dimension of 305 x 305 x 50 mm. Samples were subjected to a vertical load of 700 N from a belt sander rubber wheel flat surface, which moved forward and backward on the slab's surface with an approximate speed of 26.5 cycles per minute, see Figure 3.11. At least two replicates are required for the test. The air voids are required to be in a range of 5 ± 1%. Three replicates were prepared for each mixture of HMA, WMA and WMA-RAP using Evotherm, while two replicates were produced for each of WMA and WMA-RAP using Sylvaroad. The average air voids of the test samples of each mixture were kept in the range of 4.9–5.9%. To carry out the test, the samples were conditioned in a temperature-control chamber for 7 hours to ensure that the slab reached a constant temperature of 60°C. After conditioning, the test was started at the same temperature. During the test, the rut depth and the corresponding number of cycles were recorded. The test terminated when the rut depth reached 15 mm or the number of cycles reached 100,000, whichever occurred first.

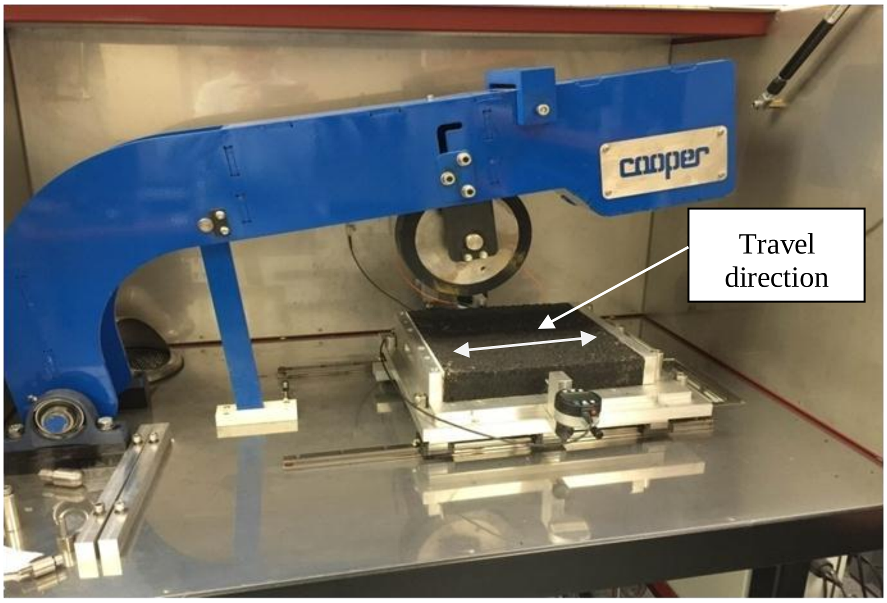

Figure 3.11 Wheel tracking set-up for rutting resistance test

3.4.7 Indirect resilient modulus test

The indirect stiffness modulus test, also called the resilient modulus test, was carried out according to AS 2891.13.1 - 1995 “Method 13.1: Determination of the resilient modulus of asphalt – Indirect tensile method” (AS/NZS). The test set-up shown in Figure 3.12 was used in this investigation. Cylindrical samples with a diameter of 150 mm and a height of 177 mm were produced. These samples were cored and sawn into samples with dimension of 100 mm in diameter and 50 ± 1 mm in height for the indirect stiffness modulus test. The air voids of samples in this research were in a range of 4.3–5.9 %. Samples were conditioned in a temperature-controlled chamber for 2 hours to reach an equilibrium temperature of 25°C before testing. During the test, haversine loads were applied along the diametrical plane of samples. The peak load and recoverable horizontal deformation of samples after applying the load were recorded to calculate the resilient modulus. The final resilient modulus of a mixture was the average of the resilient modulus values of three test replicates.

The resilient modulus derived from the indirect tensile test was calculated as shown in Equation 3.2:

$$M_r = P \times \frac{(\nu + 0.27)}{H \times h_c} \quad \textbf{(3.2)}$$

where:

M_r = resilient modulus, MPa; P: peak load, N; ν: poisson ratio;

H = recovered horizontal deformation of sample after application of load, mm;

h_c = thickness of sample, mm.

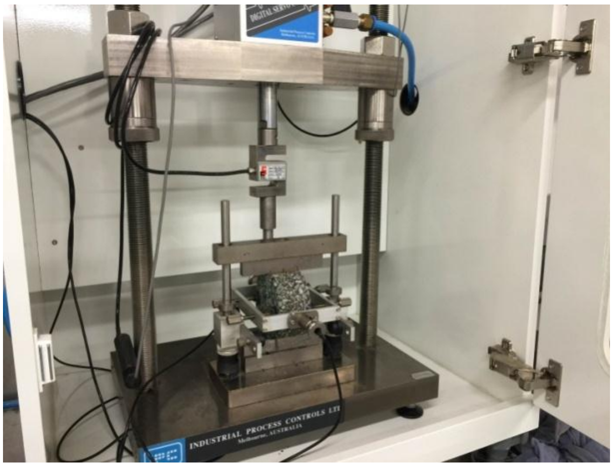

Figure 3.12 Testing set-up for resilient modulus

3.4.8 Semi-circular bending test

In this research, the SCB test was conducted to evaluate the cracking resistance of mixtures under a monotonic loading. To prepare samples for this test, cylindrical samples with a height of 177 mm and a diameter of 150 mm were produced. These samples were cored and trimmed into cylindrical samples with 100 mm diameter and 30 ± 1 mm in height. Cylindrical samples with a height of 30 mm were cut into two halves, as shown in Figure 3.13a, and notched to create samples for the SCB tests, as in Figure 3.13b. Four notch dimensions were selected in this study, including 5, 10, 15 and 20 mm with a thickness of 2 mm (Figure 3.13c). For each mixture, samples were prepared with the air void target of 5.0 ± 1% and 7.0 ± 1% for comparison. Before testing, samples were conditioned in a temperature-controlled chamber for 2 hours to reach an equilibrium temperature of 25°C. Then they were subjected to a monotonic load with the rate chosen at 1 mm/minute. The span between the two steel supports was maintained at 80 mm, as shown in Figure 3.13d, which is approximately equivalent to 0.8d (d=2r), where d is the diameter of the sample. Three replicates were prepared for each mixture at each notch length and air void target. In total, 168 samples were created for the SCB test. Critically, the selection of samples before notching was randomized to eliminate any bias and to enhance the reliability of the results.

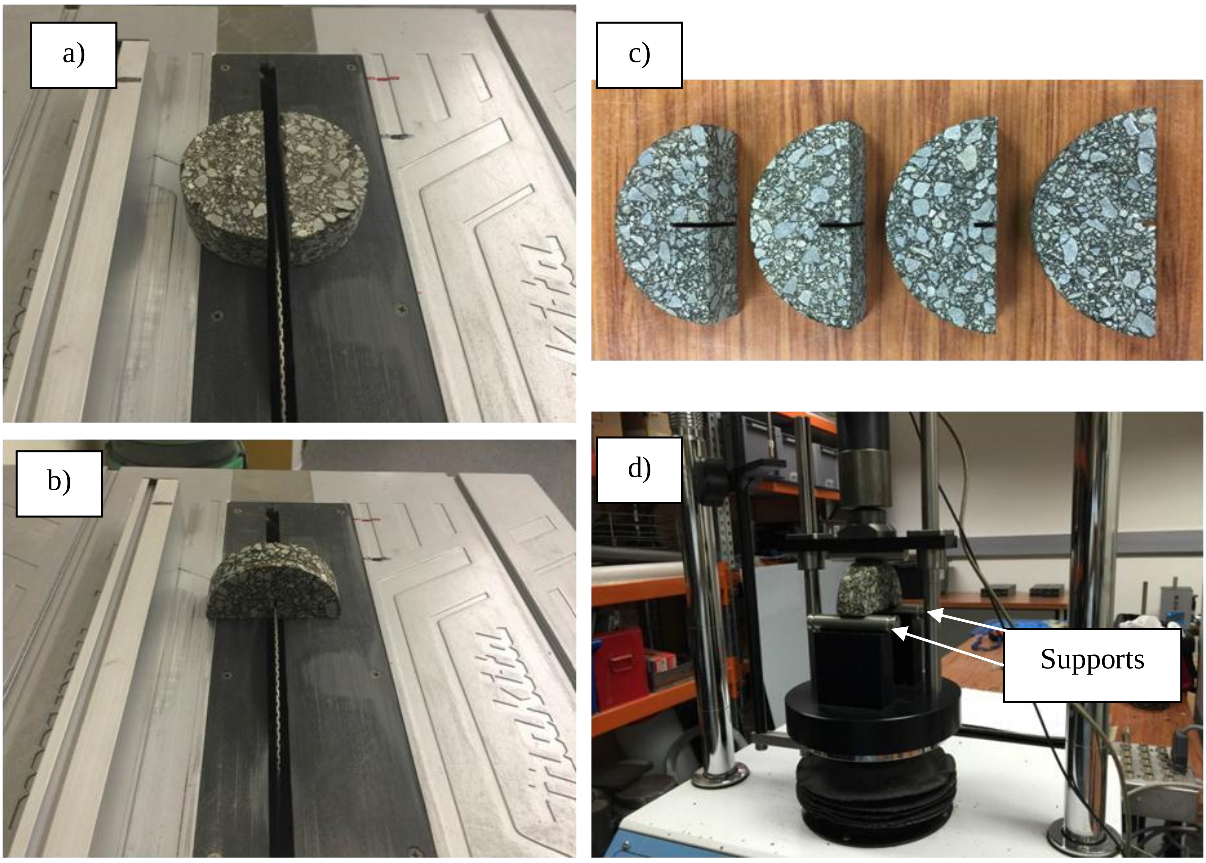

Figure 3.13 Sample preparation and testing for SCB test

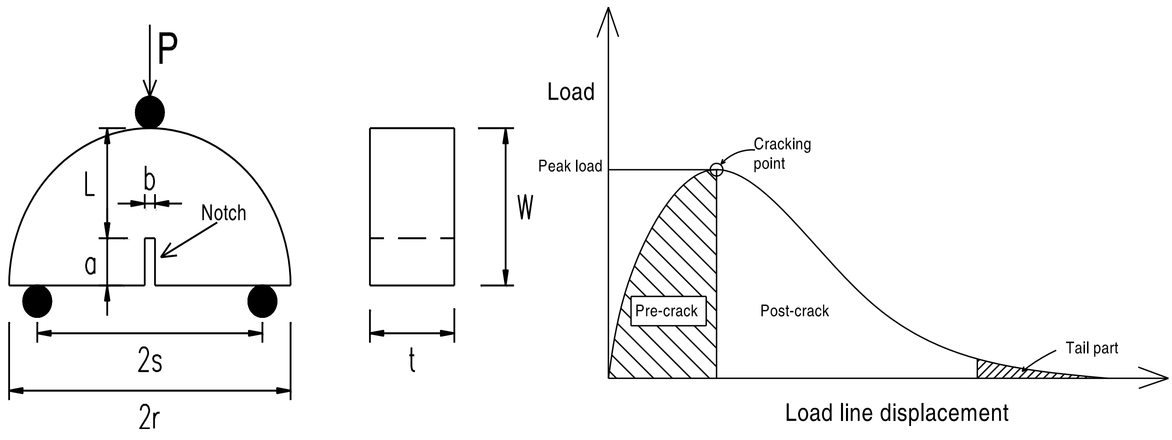

Figure 3.14 SCB test method and typical load-load line displacement plot from SCB test

In Figure 3.14, parameters are defined as below:

2r = diameter of sample (mm);

2s = span of two supports (s=0.8r) (mm);

a = notch length;

b = notch thickness;

P = load applied onto sample;

L = ligament length;

W = height of sample;

t = thickness of sample.

There were three parameters calculated from the SCB test to study the applicability of the method for 100 mm diameter samples, and the effect of notch length on the mechanical properties of the SCB test. The three parameters were maximum tensile stress (TS), fracture energy (G_f), and vertical strain at maximum load (ε_{max}).

The maximum tensile stress at the bottom of the specimen was derived from the SCB test and calculated as shown in Equation 3.3 (Arabani and Ferdowsi, 2009; Molenaar et al., 2002):

$$\sigma_m = 3564 \frac{P}{d \times t} \quad (kPa) \quad \textbf{(3.3)}$$

where

σ_m = maximum tensile stress at the bottom of specimen (kPa);

P = maximum load (N)

d = diameter of sample (=2r) (mm);

t = thickness of sample (mm).

Fracture energy is defined as the energy required from the beginning of loading until the peak load or the crack occurs. The fracture energy of the specimen was calculated from Equation 3.4:

$$G_f = \frac{W_f}{t \times L} \quad (N.mm^{-1}) \quad \textbf{(3.4)}$$

where:

W_f = fracture work or strain energy, sometimes called U (N.mm), and it is defined as the area between the load curve (up to peak load) and the load line displacement.

t = thickness of sample (mm);

L = ligament length (mm).

Vertical strain ε_m was calculated using Equation 3.5. At the maximum load, the ε_m was defined as the maximum vertical strain (ε_{max}).

$$\varepsilon_m = \frac{\Delta w_m}{W_m} \times 100\% \quad (\%) \quad \textbf{(3.5)}$$

where:

ε_m = maximum vertical strain (%);

Δw_m = vertical load line displacement at maximum load (mm);

W_m = height of sample (mm).

CHAPTER 4: RESULTS ANALYSIS

This chapter presents and discusses the results from the lab tests. As introduced in Chapter 3, tests were done to evaluate the effect of warm mix additive Evotherm and the rejuvenator additive Sylvaroad on the consistency of unaged and aged binder. Furthermore, a variety of mechanical performance evaluations of mixtures were carried out, including moisture resistance, fatigue cracking, and rutting resistance. This chapter also presents the results from the semi-circular bending test, in which the indirect tensile tests were also studied for comparison. As this project investigated nine different mixtures, in order to be consistent and to simplify the analysis of the results, a table of abbreviations of the designation names of the different mixes was created, as shown in Table 4-1.

Table 4-1 Explanation of mixtures' abbreviation

Mixture	Abbreviation
Hot mix asphalt	HMA
Warm mix asphalt using Evotherm	WMA-E
Warm mix asphalt using Evotherm adding 25% RAP	25R-E
Warm mix asphalt using Evotherm adding 50% RAP	50R-E
Warm mix asphalt using Evotherm adding 70% RAP	70R-E
Warm mix asphalt using Sylvaroad	WMA-S
Warm mix asphalt using Sylvaroad adding 25% RAP	25R-S
Warm mix asphalt using Sylvaroad adding 50% RAP	50R-S
Warm mix asphalt using Sylvaroad adding 70% RAP	70R-S

4.1 Viscosity test

The effect of the Evotherm and Sylvaroad on both virgin and aged bitumen was investigated. The rotational viscosity at different temperatures was measured using a Brookfield viscometer. Results from the viscosity tests are shown in Tables 4-2, 4-3 and Figures 4.1 and 4.2. It can be seen clearly that both Evotherm and Sylvaroad reduced the binder's viscosity in both unaged and aged cases. Furthermore, increasing the proportions of additives decreased the binder's viscosity. In the case of unaged binder, Sylvaroad performed slightly better in viscosity reduction than Evotherm at the same additive proportions. This effect was observed for the proportions of additives used later in mixtures for mechanical performance testing: the binder with 0.5% Evotherm had a higher viscosity compared with that of the binder with 2% Sylvaroad.

In terms of aged binder, it can be seen that the binder became harder after long-term ageing. This was indicated by considerably higher viscosities of the aged binder than unaged binder at all test temperatures. Evotherm and Sylvaroad greatly reduced the binder’s viscosity. Unlike the unaged binder, Evotherm reduced the aged binder’s viscosity slightly more than Sylvaroad did at the same additive proportions. However, similarly to the unaged binder case, the aged binder with 0.5% Evotherm still showed considerably higher viscosities than when 2% Sylvaroad was added to it.

Table 4-2 Viscosity results of unaged and long-term aged binder with and without Evotherm

	Unaged binder viscosity (mPa.s)					**Aged binder viscosity (mPa.s)**				
Temp (°C)	100	115	130	145	160	100	115	130	145	160
80/100 virgin	4554	1690	728	363	198	19200	5179	1770	761	352
80/100 virgin + 0.5% Evotherm	4188	1545	677	341	182	14150	4242	1554	664	328
80/100 virgin + 1% Evotherm	3530	1350	593	306	166	11192	3500	1355	600	302
80/100 virgin + 2% Evotherm	3100	1165	520	265	N/A	N/A	3040	1189	529	273

Table 4-3 Viscosity results of unaged and long-term aged binder with and without Sylvaroad

	Unaged binder viscosity (mPa.s)					**Aged binder viscosity (mPa.s)**				
Temp (°C)	100	115	130	145	160	100	115	130	145	160
80/100 virgin	4554	1690	728	363	198	19200	5179	1770	761	352
80/100 virgin + 0.5% Sylvaroad	3888	1485	630	315	166	15550	4621	1660	733	344
80/100 virgin + 1% Sylvaroad	3588	1340	588	288	159	12250	3925	1495	650	325
80/100 virgin + 2% Sylvaroad	3095	1207	529	264	147	9892	3400	1385	630	311

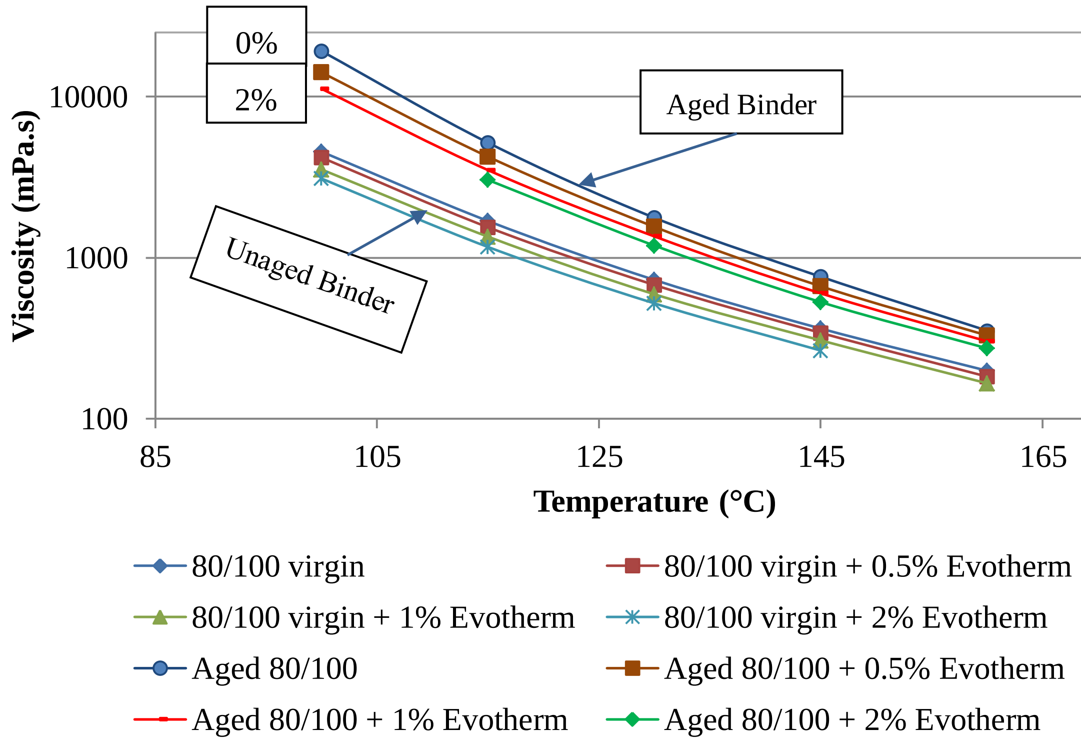

Figure 4.1 Viscosity results of unaged and long-term aged binder with and without Evotherm

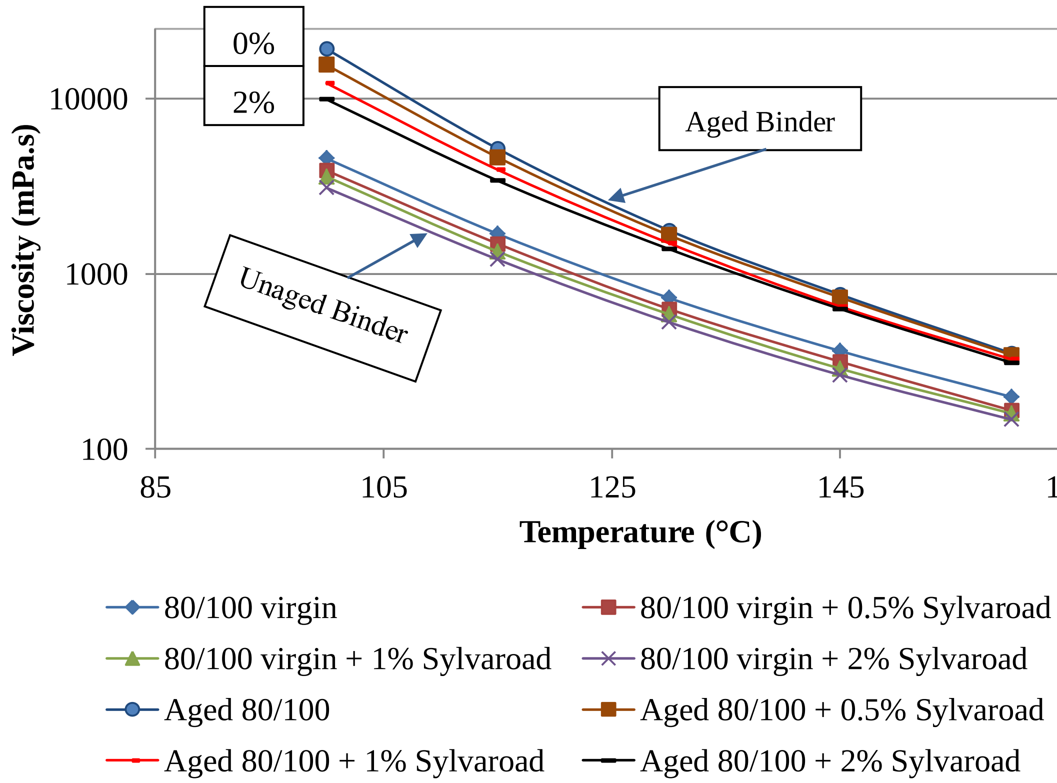

Figure 4.2 Viscosity results of unaged and long-term aged binder with and without Sylvaroad

4.2 Moisture resistance test

4.2.1 Moisture resistance of mixtures at optimum binder content and chosen additive proportions

This part presents the results from the moisture resistance test of HMA, WMA and WMA-RAP mixtures, using Evotherm and Sylvaroad. Samples used in this part were produced with the optimum binder content, as in Table 3-3, Chapter 3, and the chosen additives' proportions of 0.5% Evotherm and 2% Sylvaroad. The results of the moisture resistance test are shown in Figure 4.3. In the dry condition, it can be seen that both WMA mixtures had lower indirect tensile strengths (ITS) than HMA. With the addition of RAP, the ITS of the WMA mixtures considerably increased, becoming higher than the ITS of HMA, excluding the case of 25R-S. Furthermore, the ITS of WMA-RAP mixtures also increased with the increase in RAP content, and the ITS values of Evotherm mixtures were higher than those of Sylvaroad mixtures at the same RAP proportions.

In the wet condition, HMA had a lower ITS than expected as a control mix. The ITS of WMA-E in the wet condition reduced slightly compared with that in the dry condition, and the value was much higher than that of HMA. Similarly to HMA, WMA-S also had quite a sharp decrease in ITS, and the ITS of WMA-S was about half of the ITS value of HMA. In the wet condition, the ITS of WMA-RAP mixtures also increased with the increase of RAP content.

The moisture resistance test showed that the majority of the mixtures in this study had a lower tensile strength ratio (TSR) than 70% with the exception of WMA and WMA-RAP mixtures using Evotherm. The addition of Evotherm has remarkably improved the moisture resistance of the mixtures compared to HMA. The TSR values of both WMA-E and 25R-E exceeded

80%, whereas HMA and the mixtures with Sylvaroad had TSR values lower than 70%. Considerable stripping was observed in the cases of these mixtures, as shown in Figure 4.4.

The HMA and WMA with Sylvaroad displayed the most severe cases of stripping, while the WMA-RAP with Sylvaroad mixtures showed less stripping. The results indicate that Sylvaroad may have a negligible effect on moisture resistance of the mixtures. Conversely, when increasing the RAP proportions in the mixtures with Sylvaroad, the TSR increased. These results show that RAP might enhance the moisture resistance of mixtures. This can be explained by the fact that the bond between the binder, which is a mix of virgin binder and aged binder, and recycled aggregate is stronger than the bond between virgin binder and virgin aggregate. Thus, with the increase in RAP content, the moisture resistance of mixtures is enhanced. Similar results can also be found in the research of Zhao (Zhao et al., 2013).

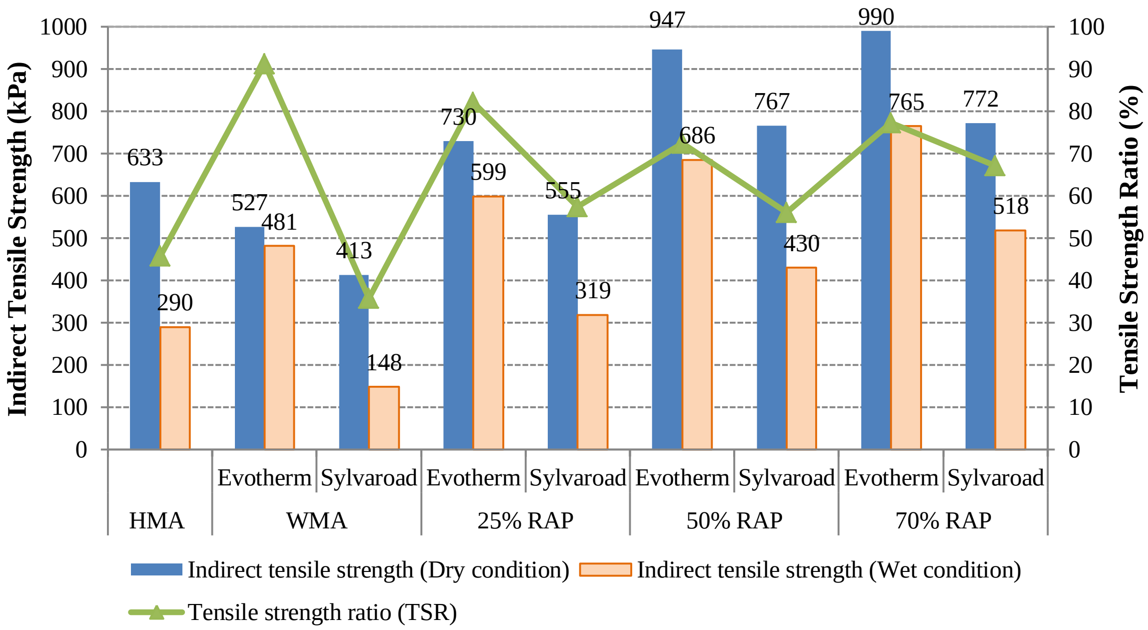

Figure 4.3 Moisture resistance test results

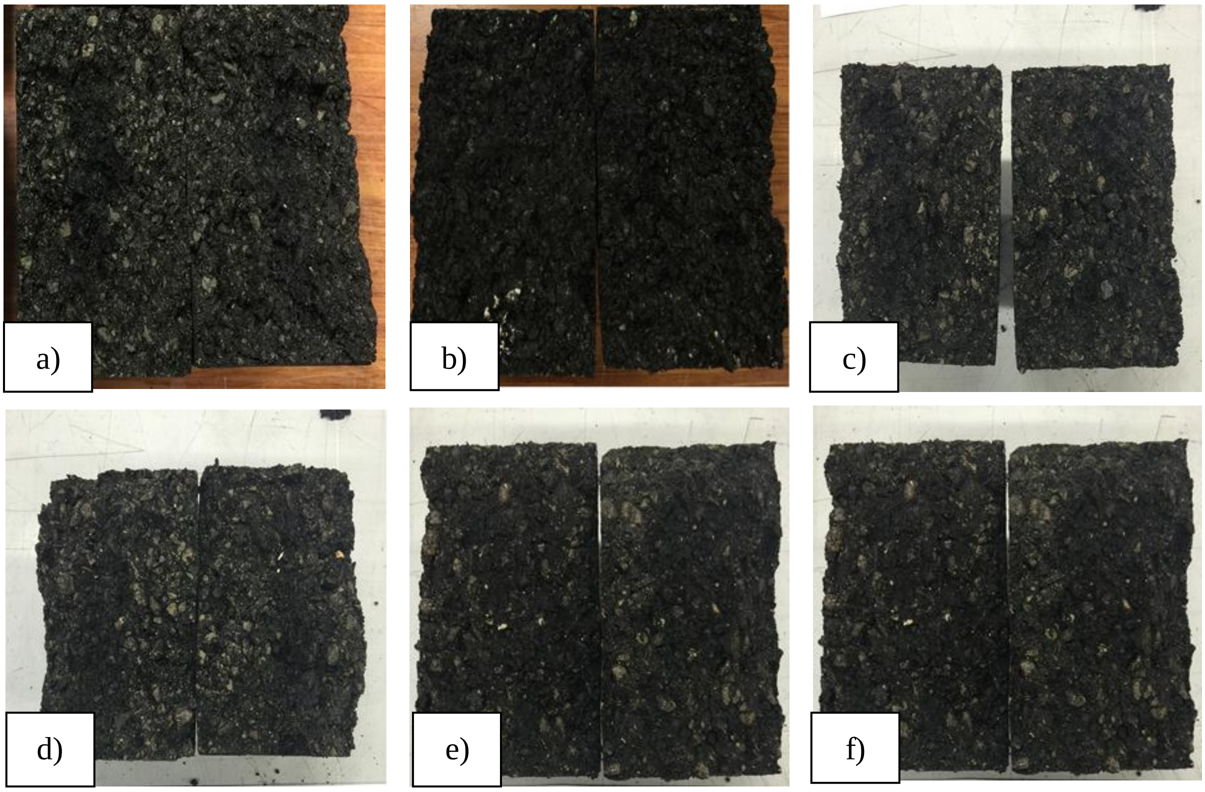

Figure 4.4 Investigation of stripping of wet subset samples after testing. a) HMA; b) WMA-Evotherm; c) WMA-Sylvaroad; d) WMA 25% RAP Sylvaroad; e) WMA 50% RAP Sylvaroad; f) WMA 70% RAP Sylvaroad

The Sylvaroad additive is still a relatively new product and there are not many publications regarding its performance. In the very latest report (Turner et al., 2015) that discusses Sylvaroad performance characteristics, the WMA mixtures with 50% of RAP were produced with and without Sylvaroad to study the moisture resistance. Sylvaroad was directly added and mixed with RAP for 30 seconds before adding virgin aggregate and binder. The results showed that the mixture with Sylvaroad was softer than the mixture without Sylvaroad. This was shown to be true in both wet and dry conditions although the TSR values were the same at 80%. There was no conclusion drawn from this study for the effect of Sylvaroad on the moisture resistance of the mixtures. The procedure used to produce mixtures with RAP and the Sylvaroad additive in the report of Turner and his co-authors(Turner et al., 2015) is different from the method used in this research project, in which Sylvaroad was added directly to the virgin binder before mixing. Nevertheless, the results from the report seem to agree with the aforementioned statement that Sylvaroad may have a negligible effect on moisture resistance of the mixtures.

4.2.2 Effect of Evotherm on the moisture resistance of WMA and WMA-RAP mixtures

Examination of stripping showed that the mixtures with higher RAP contents have a higher possibility of stripping. Aggregates with poor coating are more prone to stripping. In this study, the optimum binder content of WMA mixtures decreased with the increase in RAP contents (Table 3-3, Chapter 3). It was suspected that the binder contents in the cases of mixtures with high RAP content affect the moisture resistance of mixtures. It might be because theoretically the RAP binder would mobilize and mix with the virgin binder, coating aggregate in the mixture. However, for 12-year-old RAP, it has quite stiff binder, thus when more RAP added into the mixture and the binder content reduced, the coating of binder to aggregate would be worse. To strengthen those statements, it was decided to extend the investigation of moisture resistance to include two WMA samples modified by Evotherm and incorporating 50% and 70% RAP. The total binder contents in those mixtures were increased to 4.6%, which is equal to the optimum binder content of the WMA-25% RAP mixture.

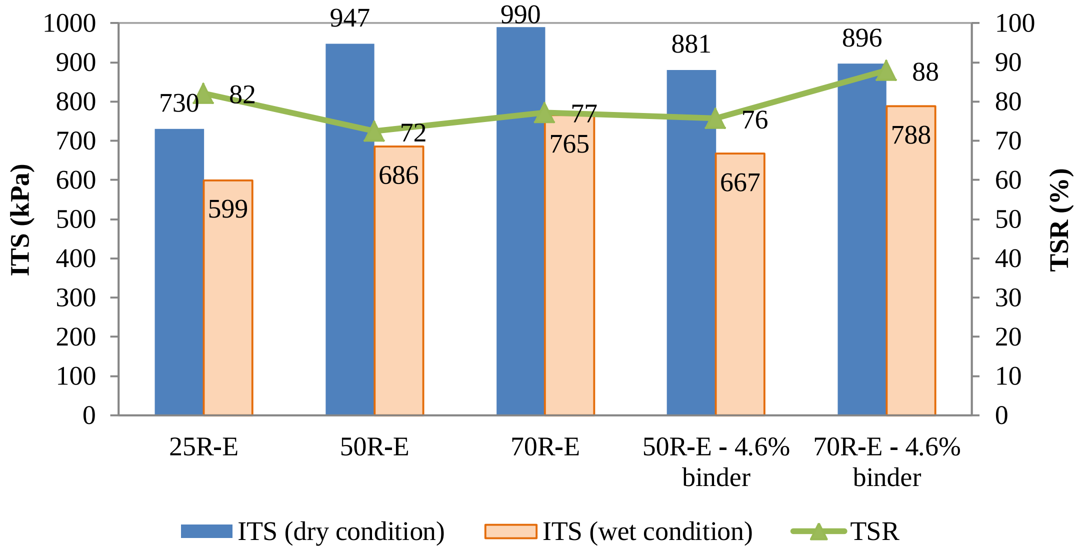

Figure 4.5 Indirect tensile strength in dry and wet conditions, and tensile strength ratios at higher binder content.

The increase in binder content reduced the ITS of mixtures in the dry condition, as can be seen in Figure 4.5. The ITS of WMA-50% RAP went down from 947 kPa to 881 kPa, while the value of WMA-70% RAP dropped from 990 kPa to 896 kPa. However, the ITS of mixtures with 50% and 70% RAP with increased binder content were still greatly higher than WMA-25% RAP mixture, in both dry and wet conditions. In the wet condition, there was a slight reduction in the indirect tensile strength of WMA-50% RAP when the binder content increased, while there was a small increase in the case of WMA-70% RAP (from 765 kPa to 788 kPa).

It can be seen that although the increase in binder content made the mixtures softer in the dry condition, the ITS of the mixtures before and after increasing the binder content were still quite similar in the wet condition. An improvement can also be seen in the TSR of mixtures after increasing the binder content. This indicates that the moisture resistance of these two mixtures, WMA-50% RAP and WMA-70% RAP, has improved. This result strengthens the aforementioned statement that the lower binder content of WMA with high RAP proportion affected the moisture resistance of those mixtures and, therefore, increasing the binder content of these mixes helps to enhance the moisture resistance.

4.2.3 Effect of Sylvaroad blended with Evotherm on the moisture resistance of WMA and WMA-RAP mixtures

From the viscosity and moisture resistance test results, it can be summarized that Sylvaroad greatly reduced the viscosity of the binder. This would help improve the coating of aggregate, especially in the case when adding high RAP content, because at lower viscosity, the binder is more mobile and thus coats the aggregate better. However, since the results from the previous part (Part 4.2.1) showed that Sylvaroad does not have a real effect on the moisture resistance of mixtures, the addition of anti-stripping additive is necessary to improve the moisture resistance of the mixtures with Sylvaroad. For this purpose, in this study Evotherm was chosen to add into the Sylvaroad mixtures as an anti-stripping additive to improve the moisture resistance. As shown by the results from the previous viscosity and moisture resistance tests, Evotherm not only increased the adhesion between aggregate and binder, but also reduced the viscosity of the binder. This was expected to help greatly improve the moisture resistance of Sylvaroad mixtures. For those reasons, the addition of Sylvaroad in the mixtures was reduced down to 1%, and the addition of Evotherm maintained at 0.5%. The reduction in Sylvaroad content was based on the expectation that the addition of Evotherm would reduce the viscosity of the binder, and thus would compensate for the reduction in the proportion of Sylvaroad.

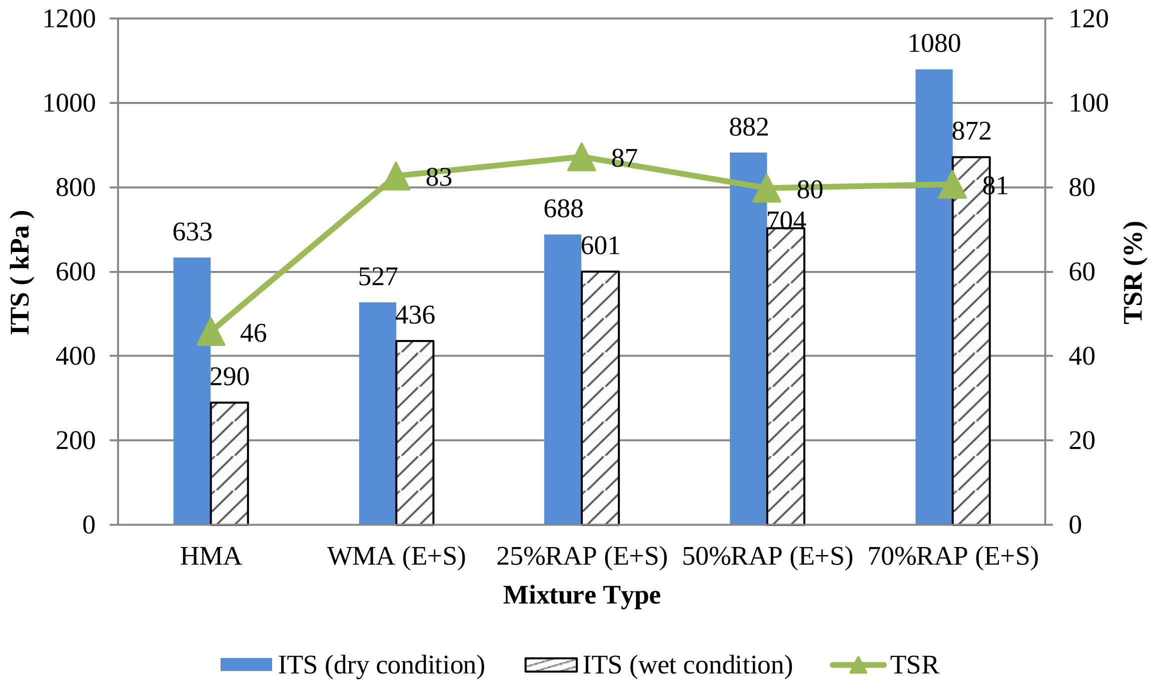

Figure 4.6 Moisture resistance results of mixtures using both Evotherm and Sylvaroad

The addition of Evotherm into Sylvaroad mixtures has improved the moisture resistance of Sylvaroad mixtures significantly, as shown in Figure 4.6. In the dry condition, compared with HMA, the WMA still showed lower ITS. The addition of RAP, however, made the mixtures harder, resulting in higher ITS values than for HMA. In the wet condition, the ITS of Sylvaroad mixtures with Evotherm increased significantly compared with the case of using only Sylvaroad. The ITS of Sylvaroad mixtures in this sample set were also greater than that of HMA, and the ITS values also increased with the increase in RAP content. All the TSR values of Sylvaroad mixtures were equal to or higher than 80%, which is the acceptable level of moisture resistance. The results indicated that the incorporation of Evotherm and Sylvaroad significantly improved the moisture resistance of WMA mixtures with high RAP content.

Although the results exhibit an important improvement in moisture resistance, this study did not investigate whether there was a chemical reaction between the two additives in the mixtures, nor how that might have affected the behaviours of the mixtures. Thus, further investigation is recommended to study the possibility of combining these two additives to improve the mechanical performance of asphalt mixes.

4.3 Fatigue test

As described in Chapter 3, fatigue tests were carried out on beams with dimensions of 50 x 65 x 405 mm. The air void target of samples was 7 ± 0.5%. All the samples were subjected to a sinusoidal load with a frequency of 10 Hz and maximum strain amplitude of 400 microstrain at 20°C. At least three replicates were tested for each mixture. The fatigue test results, including the number of cycles to fatigue failure and the initial stiffness of mixture, are described in Figure 4.7. It can be seen that the WMA-S mixture performed best with regard to fatigue resistance. All the other WMA and WMA-RAP mixtures had significantly lower numbers of cycles to reach fatigue failure than HMA had. It can also be observed from Figure 4.7 that the increase in the RAP content enhanced the flexural stiffness, but reduced the number of cycles to fatigue failure for both Evotherm and Sylvaroad mixes. This indicates that RAP made WMA stiffer and more brittle.

Within the WMA and WMA-RAP mixtures, mixtures with Sylvaroad showed better fatigue resistance compared with the corresponding Evotherm mixtures. It is clearly seen that Sylvaroad made WMA softer, therefore enhancing the flexibility of the mixture, and this improved the fatigue resistance of the mixture. It is possible that the recommended dosage of Evotherm used was not enough to achieve a similar effect to that of Sylvaroad.

In this study, the optimum binder contents of WMA and WMA-RAP were lower than that of HMA, and the optimum binder content of WMA-RAP mixtures decreased with the increase in RAP content (Table 3-3, Chapter 3). This might also be reason for the reduction in fatigue lives of mixtures when increasing the RAP content, because when the binder content increases, the thickness of the binder film between aggregates will increase, reducing the stress in the binder film (Harvey and Tsai, 1996). This enhances the fatigue life of asphalt mixtures. The increase in binder content was reported to significantly increase the fatigue life and reduce the stiffness of asphalt mixture in a report by Harvey and Tsai (Harvey and Tsai, 1996).

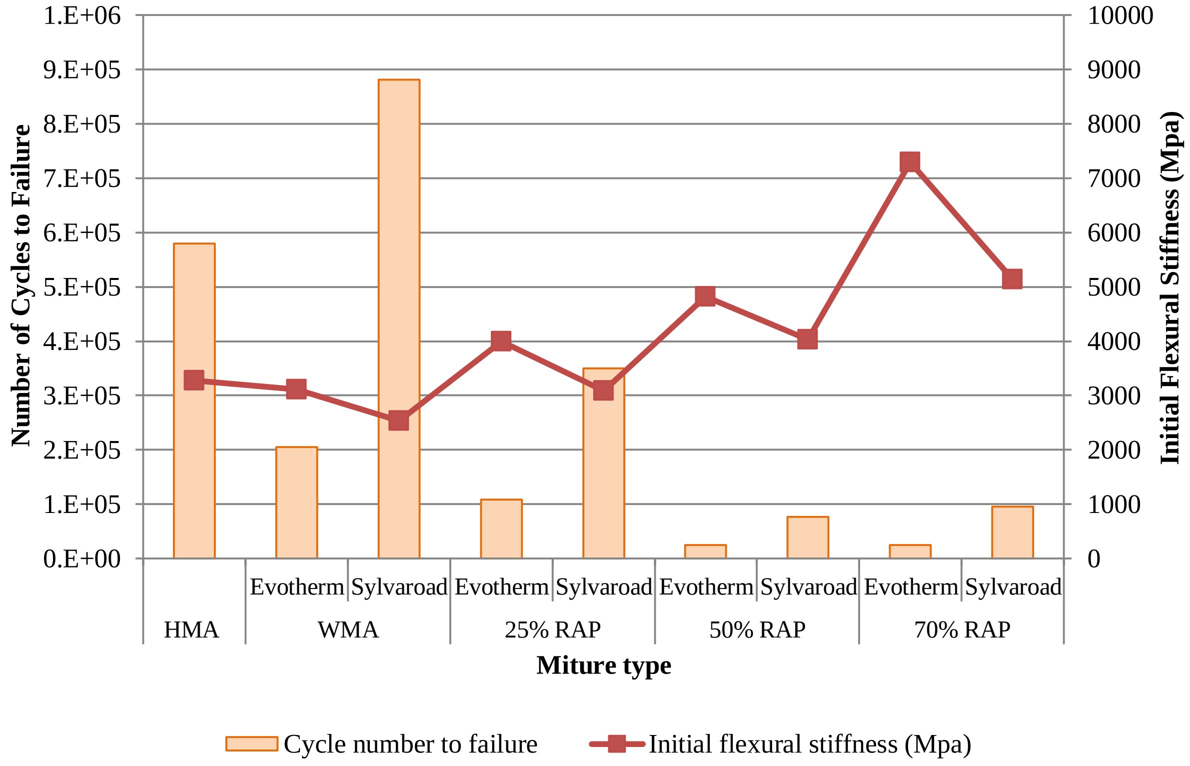

Figure 4.7 Results of four-point bending beam fatigue tests

Like the moisture resistance test, the fatigue test was also extended for the case of WMA with 50% and 70% RAP by increasing the binder content to 4.6% and using Evotherm. The average air void of WMA-50%RAP samples was 5.8%, which was lower than the testing air void target that ranged from 6.5–7.9%, while the average air void of WMA-70%RAP was 6.6%. The fatigue test results of the extended case were described in Figure 4.8. The fatigue lives of WMA with 50% and 70% RAP improved significantly with the increase in binder content. The fatigue life of WMA-50%RAP was slightly lower than that of WMA-25%RAP, and slightly higher than that of WMA-70%RAP. Because the WMA-50%RAP samples had lower air void content than the testing air void target, this might affect the fatigue life result of the mixture, since lower air void content can enhance the fatigue life of mixtures (Harvey and Tsai, 1996). However, as RAP plays an important role in the fatigue life of a mixture, and increasing RAP reduces the fatigue life of mixtures, it is expected that the WMA-50%RAP in the extended case would still have higher fatigue life than that of WMA-70%RAP if the test samples of the two mixtures had the same air void contents.

The effect of the methodology of adding Sylvaroad directly to the RAP instead of adding it to the binder will need to be further investigated. The hypothesis is that adding Sylvaroad directly to the RAP is likely to achieve better softening of the aged binder, and therefore enhance the fatigue resistance. Therefore, further investigation is recommended into the effect on fatigue performance of directly adding Sylvaroad to the RAP.

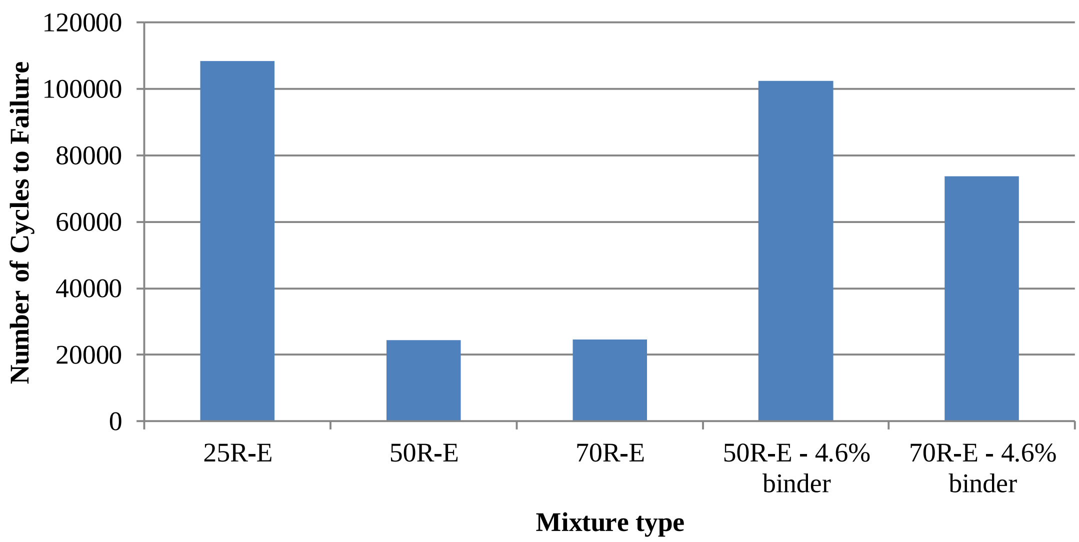

Figure 4.8 Fatigue life of mixtures at higher binder content and using Evotherm

4.4 Dynamic modulus test

The dynamic modulus test was carried out to study the rutting resistance of mixtures. The test preparation and set-up was presented in detail in Chapter 3. For each mixture, a minimum of three samples were prepared for testing, with the air void target of 5 ± 1%. The test was conducted at four different temperatures, from the lowest at 4.4°C to the highest at 50°C, and from the highest frequency of 10 Hz to the lowest frequency of 0.1 Hz. Results from the tests were used to construct the dynamic modulus master curves for mixtures at the different reference temperatures. In this research, a reference temperature of 20°C was selected. The dynamic modulus master curves for the different mixtures tested at the reference temperature are shown in Figure 4.9. It is evident that WMA-70%RAP modified by Evotherm (70R-E) had the greatest dynamic moduli over the range of tested frequencies, and the WMA-S mixture had the lowest moduli of all the mixtures. It can also be seen that WMA-RAP mixtures using Evotherm showed larger dynamic moduli than the other WMA-RAP mixtures modified by Sylvaroad at the same RAP proportions. The addition of RAP enhanced the dynamic moduli of the WMA mixtures. Most of the WMA-RAP mixtures showed greatly higher dynamic moduli than HMA, except the 25R-S mixture, which had very similar moduli to those of HMA at the frequencies ranging approximately from 0.05 to 1 Hz, and outside this range, the 25R-S's moduli were lower than those of HMA. It can also be seen that the dynamic moduli of mixtures were enhanced with the increase in RAP proportion.

There was a trend observed for WMA-RAP mixtures with Sylvaroad that they tended to have a considerable reduction in dynamic modulus when subjected to low frequency loading. All of the WMA-RAP Sylvaroad mixtures showed lower dynamic moduli than the HMA at frequencies lower than 0.0003 Hz. For mixtures without RAP, the HMA and WMA-Evotherm exhibited quite similar dynamic moduli over a large range of frequencies except when the frequencies were below 0.003 Hz. However, both HMA and WMA-E demonstrated much greater dynamic modulus values than WMA-S at all frequencies. In this study, because the lowest frequency used for testing was 0.1 Hz and the highest frequency was 10 Hz, the dynamic master curves constructed based on fitting parameters might contribute to the unexpected dynamic modulus trend of mixtures at very low and high frequencies. For that reason, the dynamic modulus trend and ranking observed in the frequency range of 0.1-10 Hz was seen to be clearer than outside this range when comparing all mixtures with HMA.

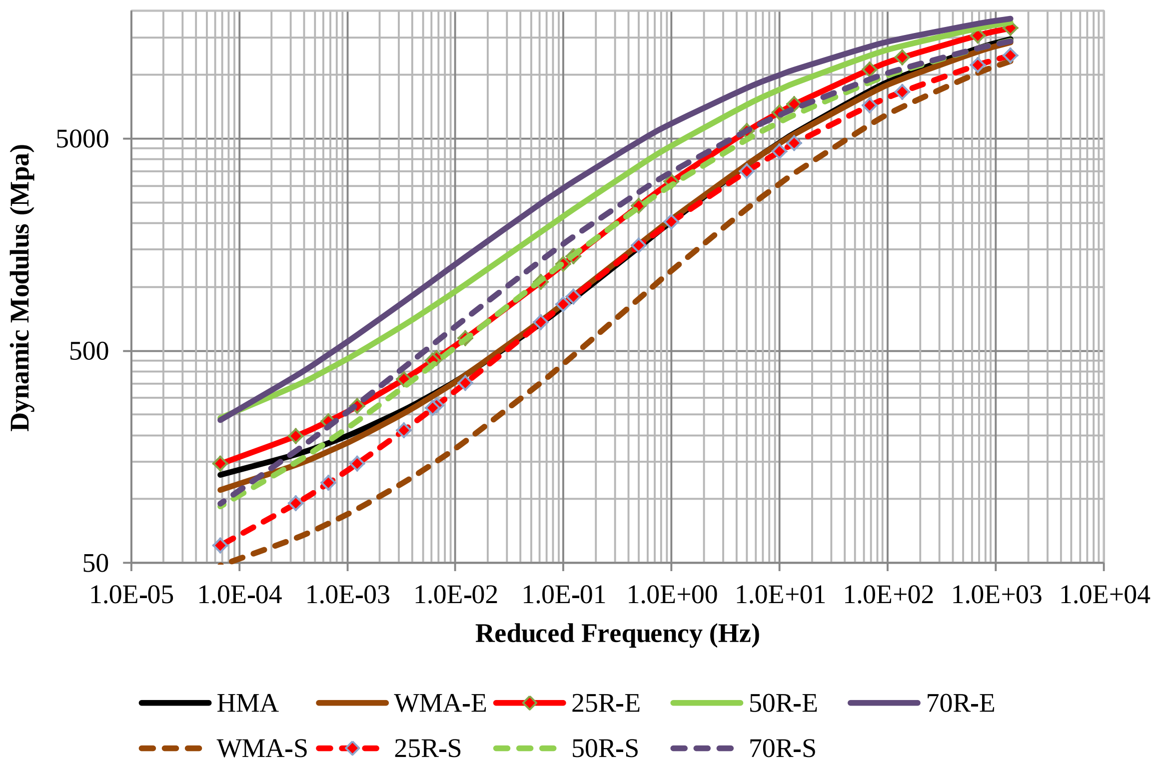

Figure 4.9 Dynamic modulus master curves of mixtures at the reference temperature of 20°C.

4.5 Dynamic creep test

The test methodology of the dynamic creep test was fully described in Chapter 3. The dynamic creep test was conducted in the unconfined mode to evaluate the rutting resistance of mixtures. The tests were carried out just after the dynamic modulus test finished, using the same samples from the dynamic modulus test, because the dynamic modulus test is a non-destructive test, so the specimens are assumed to be intact after the test. Three samples were tested for each mixture, and the tests were conducted at 50°C. The tests were terminated when either the number of load pulses reached 10,000 cycles or the strains reached 54,000 micro-strain.

Results from the dynamic creep test are shown in Figure 4.10. It can be seen that HMA exhibited better rutting resistance than the two WMA mixtures, and of them, WMA-E performed better than WMA-S. The addition of RAP significantly improved the rutting resistance of the WMA mixtures. All WMA mixtures with RAP showed considerably better rutting resistance than the control HMA. This indicates that RAP stiffened the mixture, reducing the permanent deformation of the sample during loading, and therefore improving the rutting resistance of the mixture. It can also be seen that the WMA–Evotherm mixtures performed better than WMA-Sylvaroad at the same RAP addition proportions.

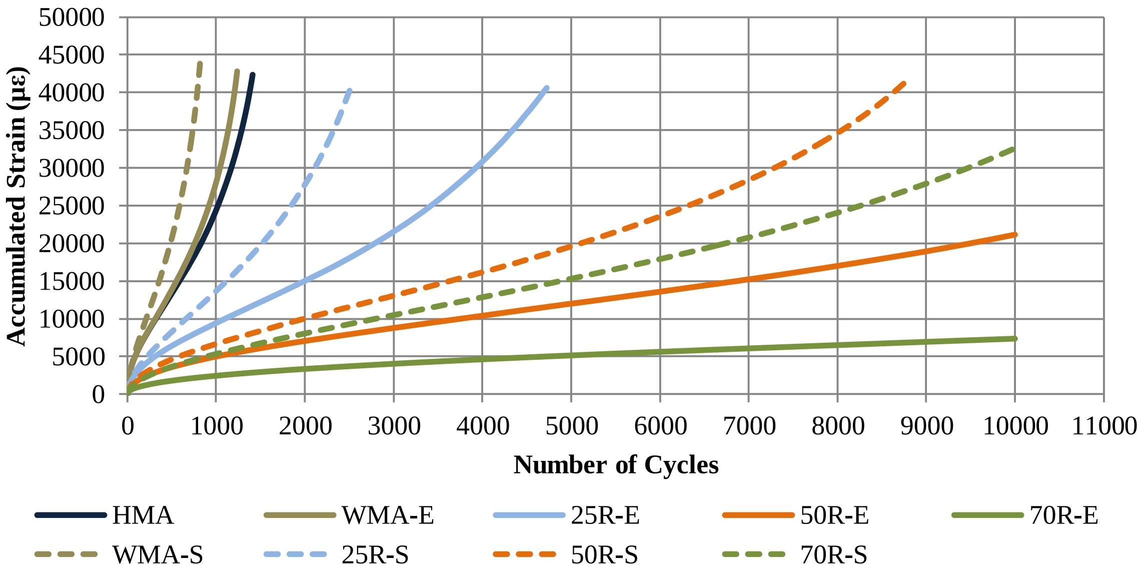

Figure 4.10 Dynamic creep test results

4.6 Wheel tracking test

In addition to the dynamic modulus and dynamic creep tests, the wheel-tracking test was carried out to evaluate the rutting resistance of the mixtures. Detailed testing preparation was presented in Chapter 3. A minimum of two slabs were tested for each mixture. The tests were conducted at 60°C. The results are shown in Figures 4.11 and 4.12.

From the two figures, 70R-E performed the best in rutting resistance compared with all other mixes, which confirms the results from the dynamic creep test and dynamic modulus test. Conversely, WMA-S had the lowest number of cycles to reach the maximum rut depth. WMA and WMA-RAP mixtures with Evotherm showed greater rutting resistance than corresponding WMA and WMA-RAP mixtures with Sylvaroad. HMA showed greater rutting resistance than the WMA mixtures, approximately twice and three times that of WMA-E and WMA-S respectively. This indicates that the binder in WMA was softer than in HMA due to lower mixing and compaction temperatures, or due to the addition of additives. For these reasons, the rutting resistances of the WMA mixtures were lower than for HMA. It is believed that the additives used might have not only reduced the viscosity of the binder at elevated temperatures, but also made the binder in compacted asphalt mixtures softer.

With the addition of RAP, all WMA mixtures showed considerable improvement in rutting resistance and were far better than HMA. The rutting resistance of WMA also improved with the increase in RAP content. By adding 25% of RAP into the WMA, the number of cycles to reach the maximum rut depth increased greatly, and the values were approximately twice that of HMA, for both Evotherm and Sylvaroad mixtures. With higher proportions of RAP, mixtures with Evotherm showed much better behaviour in rutting resistance than mixtures with Sylvaroad. At 50% RAP content, the number of cycles to the reach the maximum rut depth for the WMA mixture with Evotherm was about six times higher than HMA, while for the WMA mixture with Sylvaroad the value was roughly four times higher than HMA. At 70% RAP content, the value for WMA with Evotherm was about 21 times higher than that of HMA, and the value for WMA with Sylvaroad was approximately seven times higher than the control HMA.

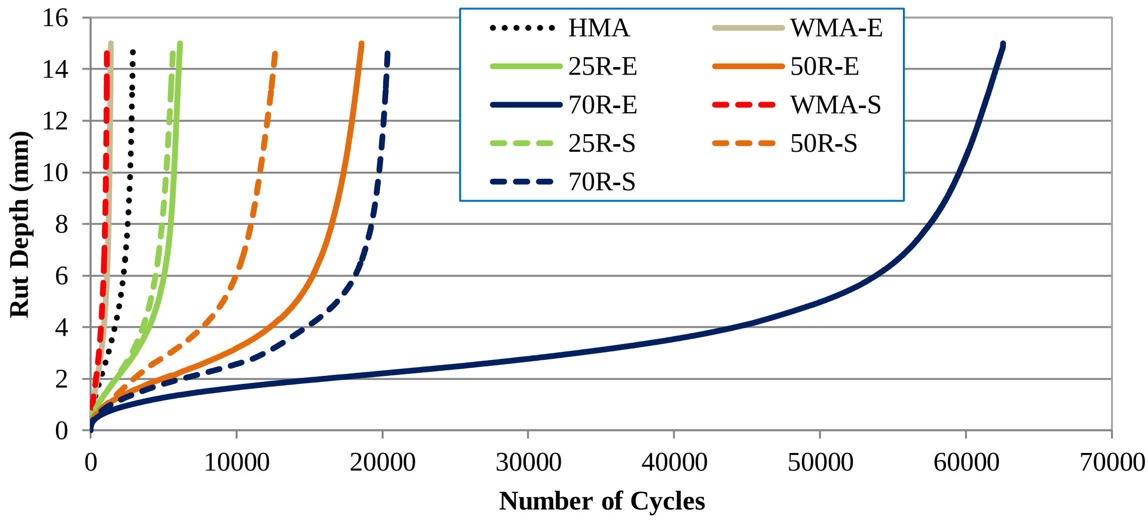

Figure 4.11 Number of cycles vs. rut depth in wheel tracking test

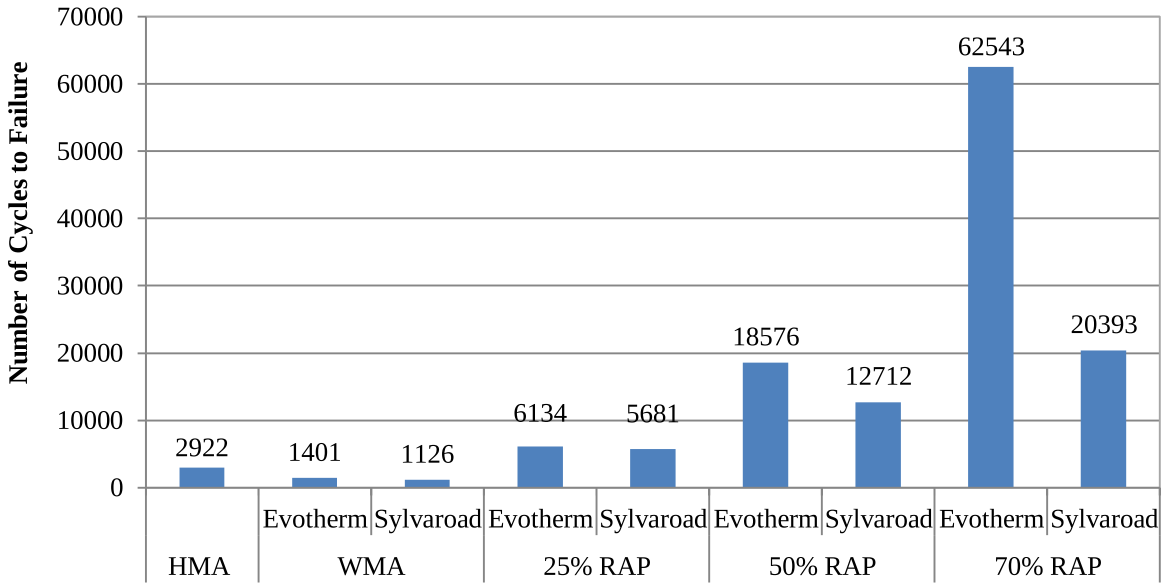

Figure 4.12 Number of cycles to reach maximum rut depth of 15 mm

The results indicate that the binder in RAP was stiff and this compensates for the softness of binder in WMA; thus the rutting resistance of WMA mixtures were improved. The binder content in the WMA-RAP mixtures might also contribute to the improvement of rutting resistance, because the optimum binder contents (Table 3-3, Chapter 3) of WMA-RAP mixtures were lower than those of HMA and WMA. However, even though the lower binder content increases the stiffness (Harvey and Tsai, 1996) and improves the rutting resistance, the effect of the binder in RAP on the mixtures is undeniable. As the binder in WMA is softer than in HMA while the binder in RAP is much stiffer, thus, the higher the proportion of RAP added to the WMA, the stiffer the binder, and the higher the rutting resistance of WMA.

Although the ranking of mixtures in rutting resistance derived from the dynamic creep test and the wheel-tracking test were quite similar, there was a slight difference in the ranking of 70R-S and 50R-E (Table 4-4). In the dynamic creep test, 50R-E showed stronger resistance to rutting than 70R-S, while in the wheel-tracking test, the trend was opposite. In this study, the samples used for the dynamic creep test were those from the dynamic modulus test, on the assumption that the dynamic modulus test is a non-destructive test; thus, the samples were assumed to be intact after the dynamic modulus test. However, minimal damage may have occurred during the dynamic modulus test (Elseifi et al., 2014), which might have contributed to the difference in ranking of the two mixtures. Another possibility is that the slabs prepared for the wheel-tracking test were compacted by a roller compactor, while cylinder samples for the dynamic creep test were compacted by a gyratory compactor. Because the two compacting regimes are different, the aggregate arrangement of samples in each regime would not be similar. This which could affect the mechanical properties of compacted asphalt mixtures. Of the two compaction types, roller compaction was reported to be able to produce samples similar to the field cores more closely than gyratory compaction (Swiertz et al., 2010).

Table 4-4 Ranking of mixtures in rutting resistance

Ranking – From weakest to strongest	Dynamic creep test	Wheel-tracking test
1	WMA-S	WMA-S
2	WMA-E	WMA-E
3	HMA	HMA
4	25R-S	25R-S
5	25R-E	25R-E
6	50R-S	50R-S
7	70R-S	50R-E
8	50R-E	70R-S
9	70R-E	70R-E

Like the moisture resistance test and fatigue test, the rutting test was extended for the cases of WMA with 50% and 70% RAP, using 4.6% binder content to evaluate the effect of the increase in binder content to rutting resistance of WMA-Evotherm mixtures with high RAP content. As can be seen in Figure 4.13, the rutting resistance of WMA with 50% and 70% RAP decreased relative to the corresponding mixtures with the optimum binder contents. But WMA with 50% and 70% RAP, using 4.6% binder content, still showed significantly greater rutting resistance than 25R-E. This result again confirms that the optimum binder content in this study greatly affected the rutting resistance of mixtures, as discussed above.

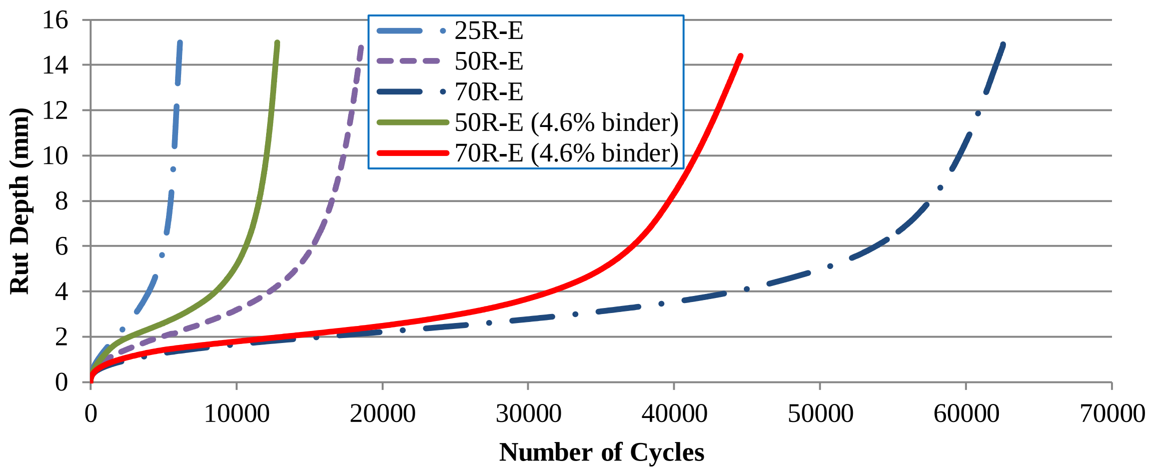

Figure 4.13 Rut depth vs. number of loading cycle with higher binder content

4.7 Evaluation of semi-circular bending test

This part of the study consists of three types of tests: resilient modulus, indirect tensile test, and semi-circular bending (SCB) test. The first two tests, resilient and indirect tensile tests, were carried out with the purpose of comparison with the SCB test. The detailed testing scheme for this part is summarized in the flowchart shown in Figure 4.14 below.

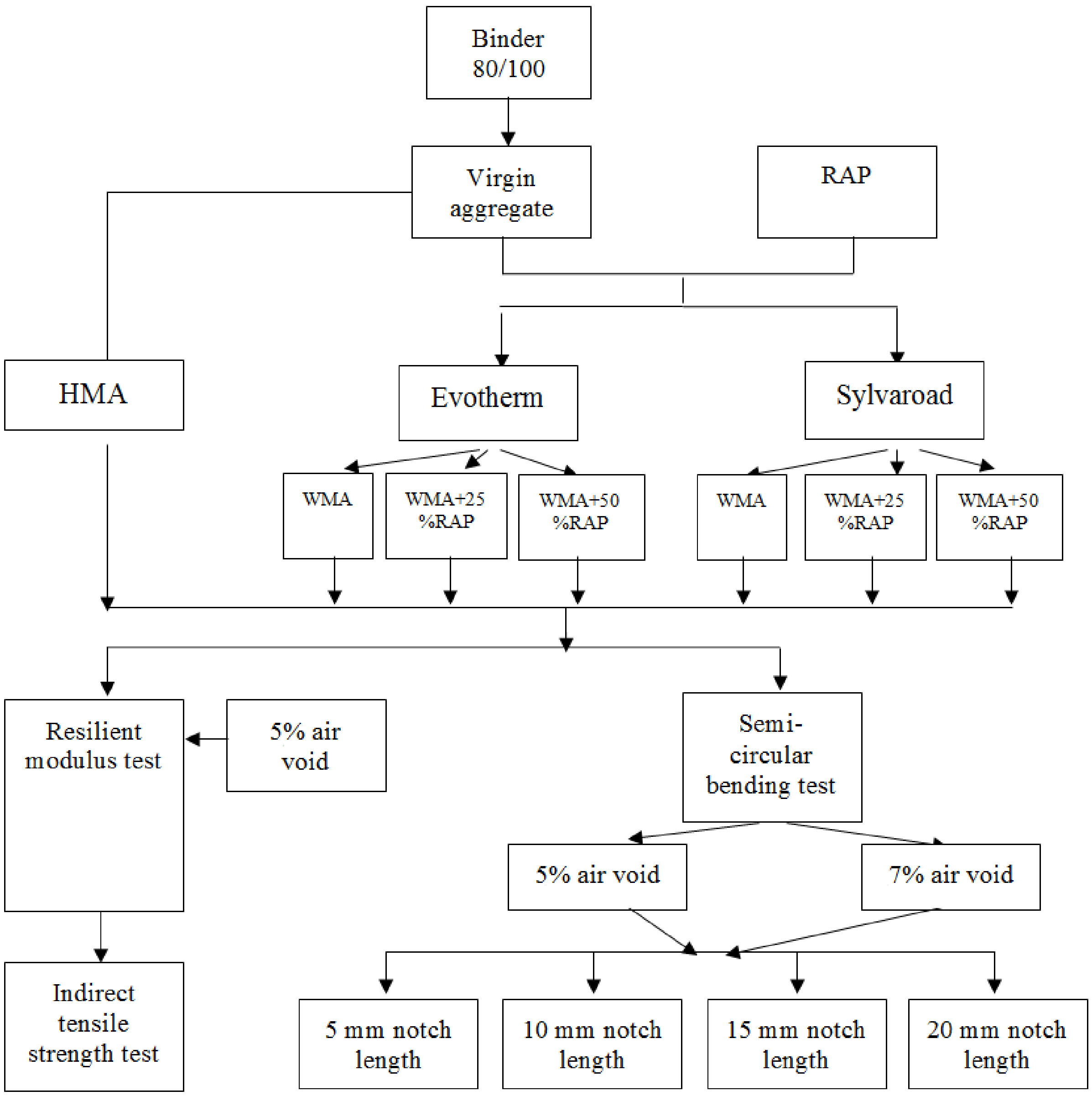

Figure 4.14 Flowchart of the testing plan

4.7.1 Applicability of the SCB test for samples with 100 mm diameter

4.7.1.1 Indirect resilient modulus and ITS results

The results from the indirect resilient modulus test and ITS tests, and the relationship between test parameters are shown in Figure 4.15. HMA had higher values of resilient modulus (M_r) and ITS than WMA had. In addition, WMA-E showed greater values of M_r and ITS than WMA-S did. Increasing RAP enhanced M_r and ITS linearly in both cases of Sylvaroad and Evotherm. ITS and M_r in this research showed a linear relationship, indicating that the two indirect tensile tests were quite consistent with each other, and could become reliable values for comparison with values from the SCB test.

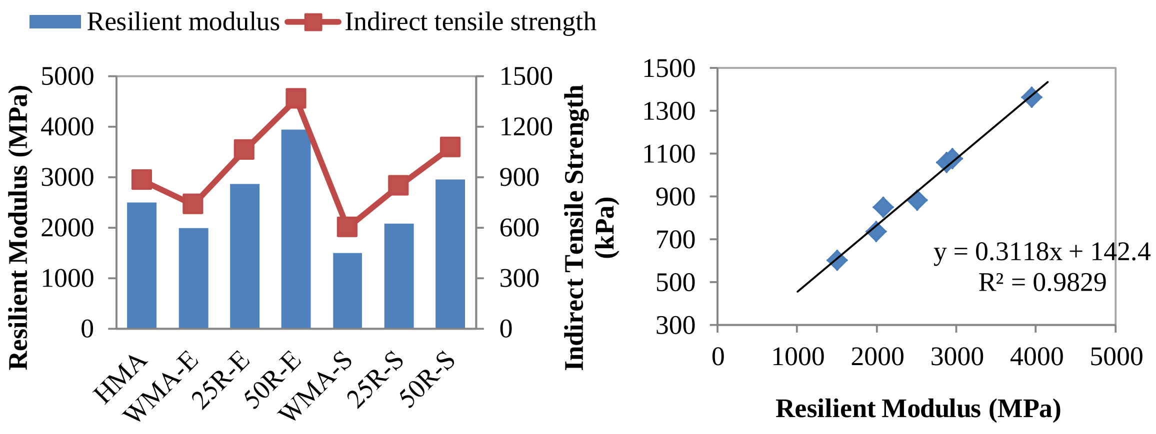

Figure 4.15 Resilient modulus and indirect tensile strength test results and the relationship between them

4.7.1.2 Maximum stress at failure of SCB test

The tensile strength is an important parameter in pavement design as the tensile strength can be used to evaluate the mechanical behaviour of asphalt mixtures. Like the IDT test, the SCB test was used to measure the tensile strength of asphalt mixtures. In this study, the term *maximum tensile stress* was used and abbreviated as TS. Figure 4.16 shows the results of TS achieved from the SCB test. It can be seen that the TS reduced with the increase in notch length and air void. Only one exception was observed in the case of WMA-E mixture prepared with 7% air void, in which the TS of samples prepared with 10 mm notch length was slightly smaller than that of 15 mm notch length samples. It might be because the SCB test for small sample size was sensitive to the air void, which led to some variation in the results. However, the TS values in the SCB tests generally exhibited very similar trends to that of the IDT tests, indicating the SCB test has great promise as an alternative to the IDT test to indicate the tensile strength properties of asphalt materials.

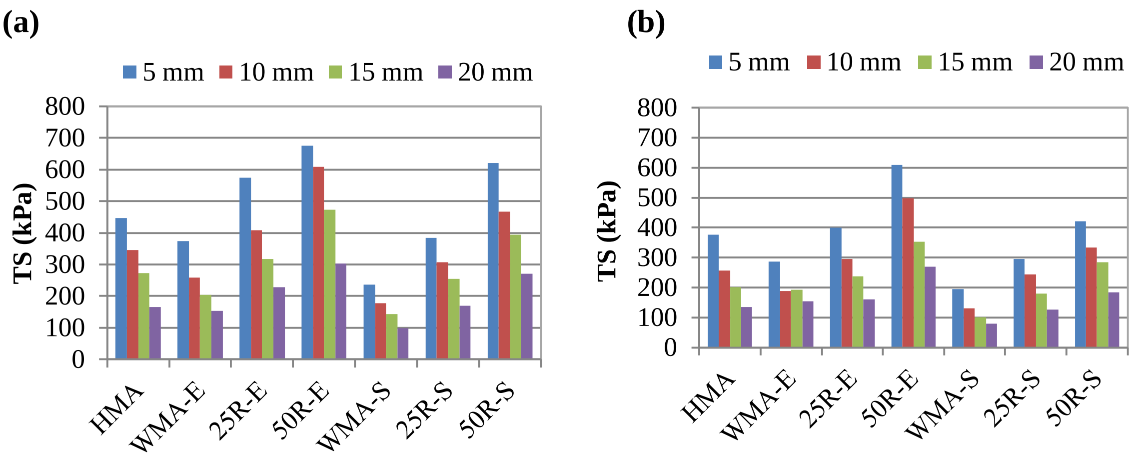

Figure 4.16 Maximum tensile stress of mixtures. (a) 5% air void; (b) 7% air void

4.7.1.3 Comparison between SCB test parameters and resilient modulus and ITS values

The comparison between the indirect resilient modulus, ITS tests and SCB test was based on the repeatability of each test, and the correlation between their values. The repeatability was evaluated by using the coefficient of variation (CoV) parameter. CoV values lower than 25% were considered a sufficient level of repeatability of the test (Li and Marasteanu, 2010). The

CoV values of results from tests in this study are shown in Table 4-5. It can be seen from Table 4-5 that all the tests had average CoV values lower than 25%, indicating that the tests satisfied the repeatability requirement. Of the tests, SCB tests showed comparable repeatability with indirect resilient modulus and ITS tests, with the average CoV values being rather similar. The results also showed that mixtures with RAP normally showed higher variation in results than mixtures without RAP, regardless of test methods. That could be explained because samples were cored and cut from bigger cylinders; thus some samples might have more RAP content than others, as RAP might not spread homogeneously in the samples. The sample with more RAP would be harder, resulting in different results from the sample with less RAP. This situation was more sensitive in the case of the SCB test, as the thickness of the samples was 30 mm, which was smaller than for the resilient modulus and ITS samples of 50 mm. This could be a reason for the relatively high CoV in some cases of the SCB tests, such as 50R-S with 5 mm notch length – 5% air void.

Table 4-5 Coefficient of variation (%) of M_r, ITS and TS results

Mixture type/air void (%)	M_r	ITS	TS (SCB)							
			5 mm		**10 mm**		**15 mm**		**20 mm**	
			5	**7**	**5**	**7**	**5**	**7**	**5**	**7**
HMA	0.9	1	10.3	5.5	4.3	3.8	9.4	6.2	6	15.8
WMA-E	4	2.9	6.3	1.8	3	4.1	3.8	13.4	9	8.4
25R-E	7.1	3.9	7.2	2.6	7.4	7.8	9.8	16	5	13
50R-E	15.7	10.8	2.8	13.5	2.7	7.8	15.2	4.1	4	4.4
WMA-S	10.9	7.3	7.8	1.2	6.6	2.9	15	9.9	7.6	11.8
25R-S	6.6	1.9	5.4	0.1	15.5	17.7	3	12.5	6.5	2.9
50R-S	17.6	14.7	32.2	5.4	3	16.6	23.5	12.5	6.9	4.1
Average	**9.0**	**6.1**	**10.3**	**4.3**	**6.1**	**8.7**	**11.4**	**10.7**	**6.4**	**8.6**

Another important investigation of the applicability of the SCB test for the 100 mm diameter samples is whether values of ITS and TS are correlated. The ratios of ITS to TS were calculated for each mixture and for each notch length and air void target. The detailed results are shown in Table 4-6 and plotted in Figure 4.17 for each air void target. As can be seen from Table 4-6, at each air void content for each notch length, the ratio of ITS/TS for each mixture had high agreement with others, indicating CoV values lower than 25%. The results indicate that ITS and TS are correlated, meaning that the SCB test can be used for determining the tensile strength of asphalt mixtures, instead of using the ITS test. In this study, it should be noted that the ITS/TS values were larger than 1 because of a few reasons. Firstly, the TS of the SCB test is not the tensile strength derived from the test, as the true tensile strength can be achieved from the un-notched SCB samples. That the thickness of the SCB samples was smaller than those of the ITS test also affected the results. Moreover, the stress status in the two tests was different. The ITS test had a complicated stress state compared to that in the SCB test.

Table 4-6 Ratio of ITS and TS

Notch depth	**5 mm**		**10 mm**		**15 mm**		**20 mm**	
Mixture / Air void (%)	5	7	5	7	5	7	5	7
HMA	1.97	2.35	2.55	3.43	3.23	4.37	5.34	6.56
WMA-E	1.97	2.57	2.85	3.91	3.62	3.82	4.81	4.81
25R-E	1.85	2.65	2.60	3.58	3.34	4.47	4.63	6.63
50R-E	2.02	2.24	2.24	2.73	2.88	3.87	4.49	5.06
WMA-S	2.54	3.08	3.40	4.60	4.19	6.01	6.05	7.58
25R-S	2.21	2.88	2.76	3.49	3.33	4.71	4.98	6.75
50R-S	1.37	2.02	1.82	2.54	2.15	2.99	3.13	4.63
Average	**1.99**	**2.54**	**2.60**	**3.47**	**3.25**	**4.32**	**4.78**	**6.00**
CoV(%)	**17.8**	**14.5**	**19.0**	**20.1**	**19.3**	**21.7**	**18.7**	**19.1**

The results also showed that TS reduced with an increase in air void and notch length: the ratio of ITS/TS increased with an increase of notch length and air void, as shown in Figure 4.17. It can also be seen from Figure 4.17 that for each air void target of SCB, the ratio of ITS/TS versus notch length did not follow a linear trend, but showed a positive correlation.

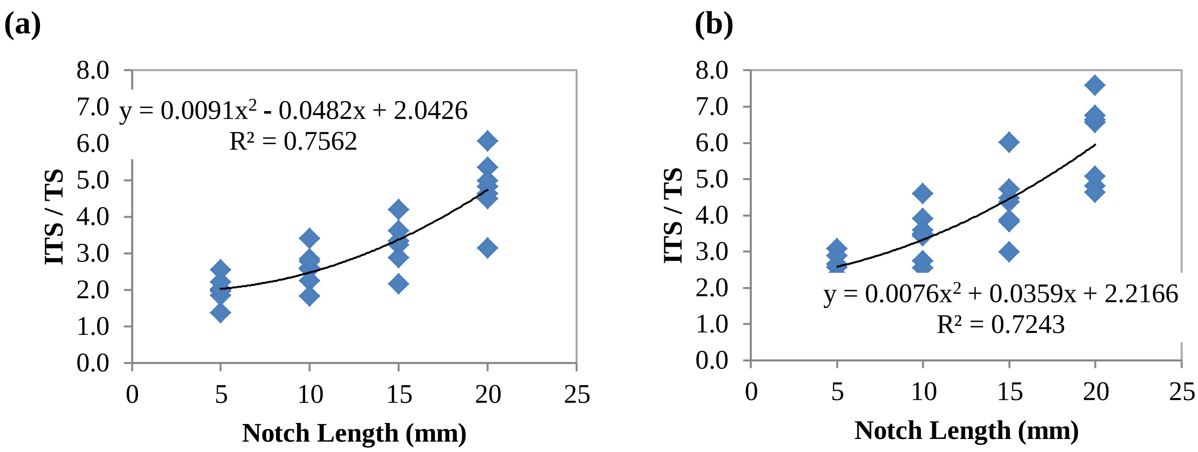

Figure 4.17 ITS/TS ratios. (a) Samples of SCB test with 5% air void; (b) Samples of SCB test with 7% air void

4.7.2 The effect of notch length on the mechanical properties of SCB test

As the above part proved, the 100 mm diameter samples were applicable for the SCB test to indicate the tensile strength properties of asphalt mixtures. This part will focus on the investigation of the effect of notch length on the mechanical properties of the SCB test, including fracture energy and vertical strain at maximum load.

4.7.2.1 Consistency of results

This part presents the consistency of SCB test results: fracture energy (G_f) and vertical strain at maximum load (ε_{max}). The consistency of parameters G_f and ε_{max} was evaluated via CoV values as shown in Table 4-7. It can be seen that all the average CoV values were lower than 25%, meaning that they were at an acceptable level of consistency, regardless of notch length, air void and mechanical parameters. There were a few CoV values higher than 25%, in the cases of mixtures with virgin aggregate as well as with RAP. This situation was more likely to happen in the cases of G_f and RAP mixtures. As per Equation 3-4, G_f depends on b, L and W_f. Because the values of b and L were very much constant for each notch length, the result of G_f

was mainly affected by W_f. The value of W_f is dependent on the load and strain. The dependence of W_f on two variables may increase the chance of the final W_f having higher variation than would parameters calculated from only one variable.

As discussed before, high RAP content may result in higher variation than for mixtures with virgin aggregate. If the distribution of the RAP in the mix is not homogenous, there will be a higher chance for large variability in the SCB test results.

Table 4-7 Coefficient of variation of SCB mechanical properties

Notch length	**5 mm**		**10 mm**		**15 mm**		**20 mm**	
Mixture / Air void (%)	**5**	**7**	**5**	**7**	**5**	**7**	**5**	**7**
	CoV of fracture energy (%)							
HMA	11.3	3.8	4.1	4.0	4.6	9.0	1.5	18.5
WMA-E	6.5	5.6	23.9	16.7	5.9	10.2	15.0	14.4
25R-E	1.6	7.8	13.2	5.5	11.5	22.1	14.9	20.2
50R-E	4.7	22.0	8.1	21.1	29.7	9.7	17.7	11.3
WMA-S	20.8	16.3	26.7	10.8	22.4	15.8	14.8	35.0
25R-S	15.1	9.4	15.0	24.6	2.6	23.0	18.7	14.3
50R-S	47.5	14.0	7.7	7.6	42.0	18.1	4.0	4.5
Average	**15.4**	**11.3**	**14.1**	**12.9**	**17.0**	**15.4**	**12.4**	**16.9**
	CoV of strain (%)							
HMA	1.3	6.0	8.9	4.1	9.8	0.4	4.0	0.5
WMA-E	8.0	4.5	18.9	12.2	4.2	8.4	9.0	9.0
25R-E	8.3	3.9	16.9	6.2	1.9	7.5	9.2	17.3
50R-E	9.9	9.0	11.2	12.0	10.7	8.5	17.6	11.6
WMA-S	10.2	14.9	22.1	7.3	8.3	4.8	8.1	24.6
25R-S	11.7	9.0	6.0	6.3	4.5	10.9	15.9	11.8
50R-S	23.5	6.3	7.2	7.8	21.8	14.9	1.1	1.7
Average	**10.4**	**7.7**	**13.0**	**8.0**	**8.7**	**7.9**	**9.3**	**10.9**

4.7.2.2 Fracture energy G_f

The fracture energy, G_f , of mixtures at different notch lengths and air voids are shown in Figure 4.18. The G_f indicates the energy required to fracture the sample. Higher G_f values can be understood as higher fracture resistance. In this study, a few general trends can be observed. The G_f of samples with higher notch length was lower than samples of the same mixtures with smaller notch length (Figure 4.18(a,b)). This can be explained because higher notch length samples had lower ligament area, meaning that they had lower energy to resist fracture. Another trend observed was that increasing air void results in lower G_f, because samples with lower air void were stiffer and stronger in resisting loading (Figure 4.18(c,d)). HMA was observed to perform better than WMA mixtures. Furthermore, the addition of RAP improved G_f regardless of WMA technologies, indicating that the fracture resistance of WMA-RAP mixtures was improved. The results indicate that RAP makes WMA stiffer; thus they become stronger in terms of fracture resistance.

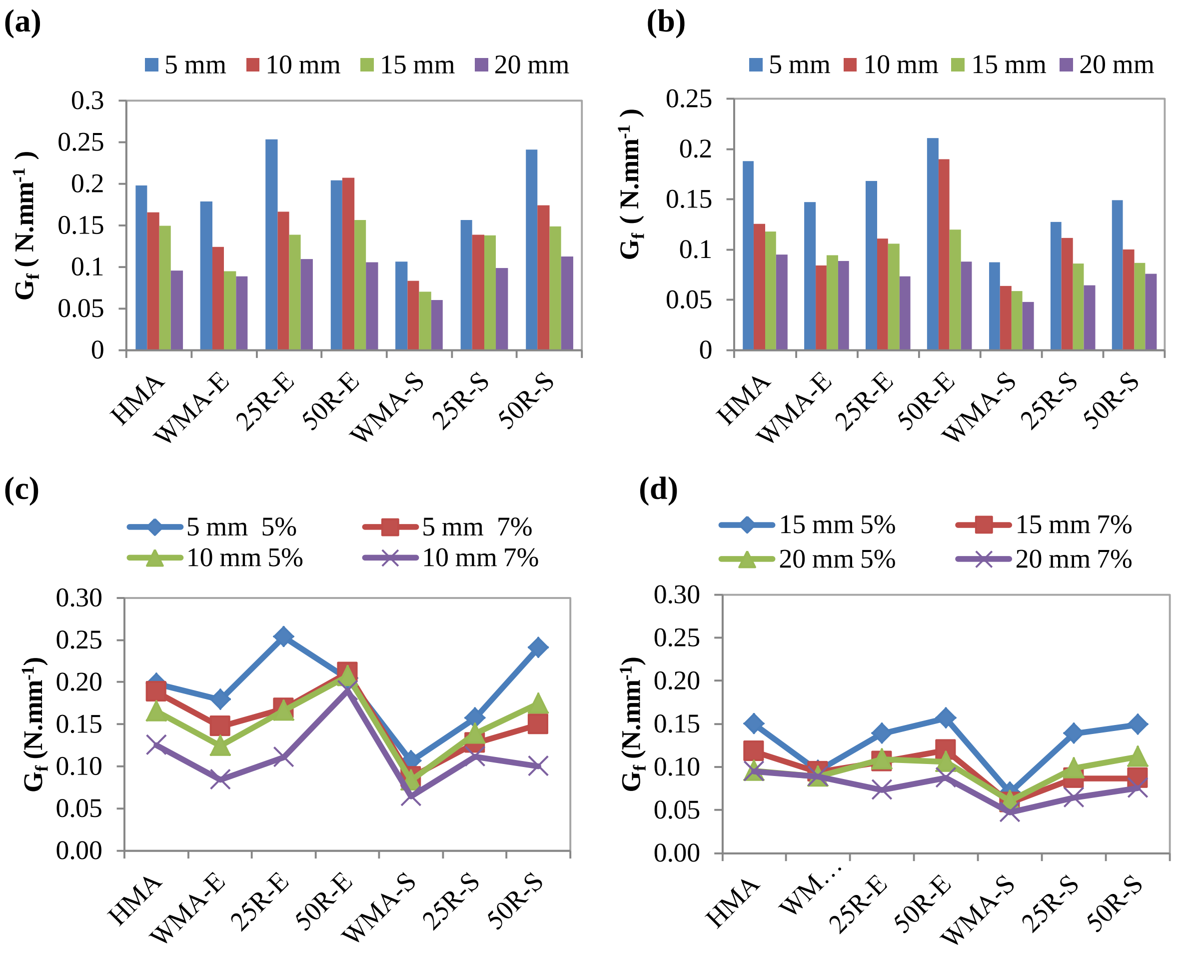

Figure 4.18 Fracture energy of mixtures. (a) 5% air void; (b) 7% air void

4.7.2.3 Vertical strain at maximum load ε_{max}

When the applied load on the sample reaches its peak, the horizontal tensile stress reaches its maximum value; this is called maximum tensile stress (TS). Also at that point, another important parameter can be obtained which is the maximum vertical strain ε_{max}, which is the percentage of the displacement to the height of the sample. Since the ε_{max} value shows the flexibility of an asphalt mixture (how much deformation that asphalt sample can stand before cracking), it was identified as an important property and thus ε_{max} was investigated in this study. The results of ε_{max} are shown in Figure 4.19. It can be seen that the ε_{max} of different notch lengths of the same mixtures did not show a clear trend, regardless of air void, although the ε_{max} seemed to reduce with an increase in notch length. There were a few cases where the ε_{max} of samples with higher notch length were similar to or slightly greater than those of samples with smaller notch lengths. This situation was more likely to happen in the case of mixtures with 7% air void than that of 5% air voids. Samples with lower air voids not only produce a more homogeneous aggregate asphalt structure but also create fewer and smaller voids, which are more evenly distributed (Harvey and Tsai, 1996). Therefore, it is more likely that samples with 7% air voids create results with more discrepancies from the general trend than do samples with 5% air voids.

Comparing the mixtures, the ε_{max} of WMA reduced when higher RAP content was added, for both cases of air void. HMA also had a slightly higher ε_{max} value than WMA-E and WMA-S, more obviously in the case of 5% air void. The results indicate that RAP stiffened the mixtures, but made them less flexible, therefore resulting in lower ε_{max}.

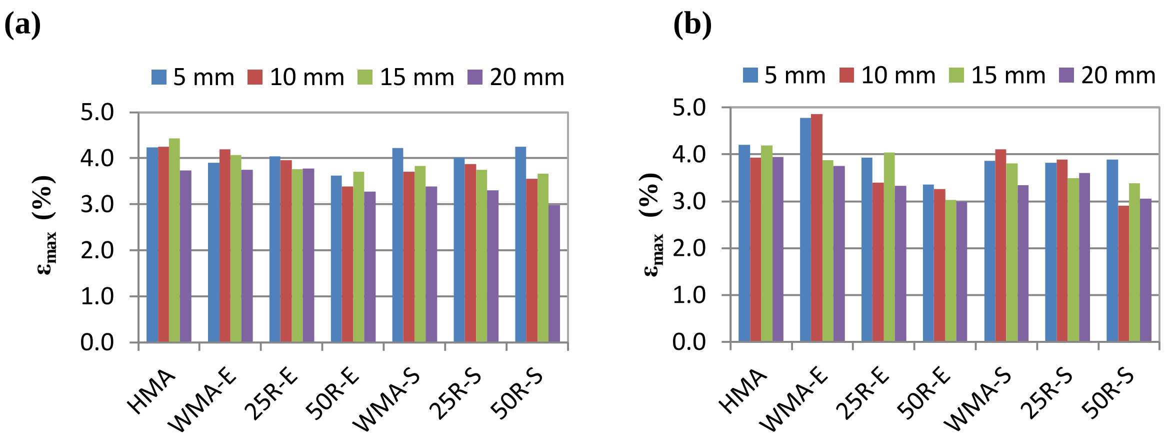

Figure 4.19 Vertical strain at maximum load of mixtures. (a) 5% air voids; (b) 7% air void

4.7.2.4 Visual examination of testing samples

Visual observation of samples after testing was also done to examine the nature of cracks and how they affected the G_f, TS, and ε_{max} of mixtures. Three typical samples for each notch length are shown in Figure 4.20 for illustration. Some examples of samples with 5 mm notch length were seen to have more than one crack (Figure 4.20(5-a)), or the crack did not start from the notch tip (Figure 4.20(5-c)). In these cases, the cracking ligament area would be larger than in the case where only one crack occurred and started at the notch tip to the loading strip. This phenomenon led to a higher fracture energy, increasing the variation of the final results. This can be attributed to the fact that the notch length was too short to lead the crack well. Although this situation occurred in some situations, it might have contributed to some of the uncommon, high CoV values of the SCB test results. However, on looking back to the CoV values from the SCB test results in Tables 4-5 and 4-7, it can be seen that only the 50R-S mix had CoV values of TS and G_f higher than 25%. Hence, a 5 mm notch length for the SCB test with 100 mm diameter samples should only be used with care, ensuring that samples with cracks that initiated away from the notch tip should be eliminated and replaced by others.

For samples with 10 and 15 mm notch length, cracks started nicely from the notch tip, and ran to the loading strip. In the case of samples with 20 mm notch length, a few cases of crack started from the notch tip but finished not at the loading strip as in Figure 4.20(20-b,c), although the CoV values for the 20 mm notch length samples (Tables 4-5 and 4-7), were very similar to those for other notch lengths. Cracks like those for the 20 mm notch length are not preferred, however, as the cracks showed that tensile stress was not really largest along the line from the notch tip to the loading strip. There was a concern that the 20 mm notch depth might be too deep, or not suitable for samples of 100 mm diameter, as the combination of 30 mm thickness and approximately 30 mm ligament length yielded a ligament area of 900 mm^2, which might be too small to reflect the material characteristics. The results indicate that a thickness of 30 mm should be the minimum value that should be used for a SCB test prepared with 100 mm diameter specimens. In addition, a 20 mm notch length is not recommended for 100 mm diameter specimens.

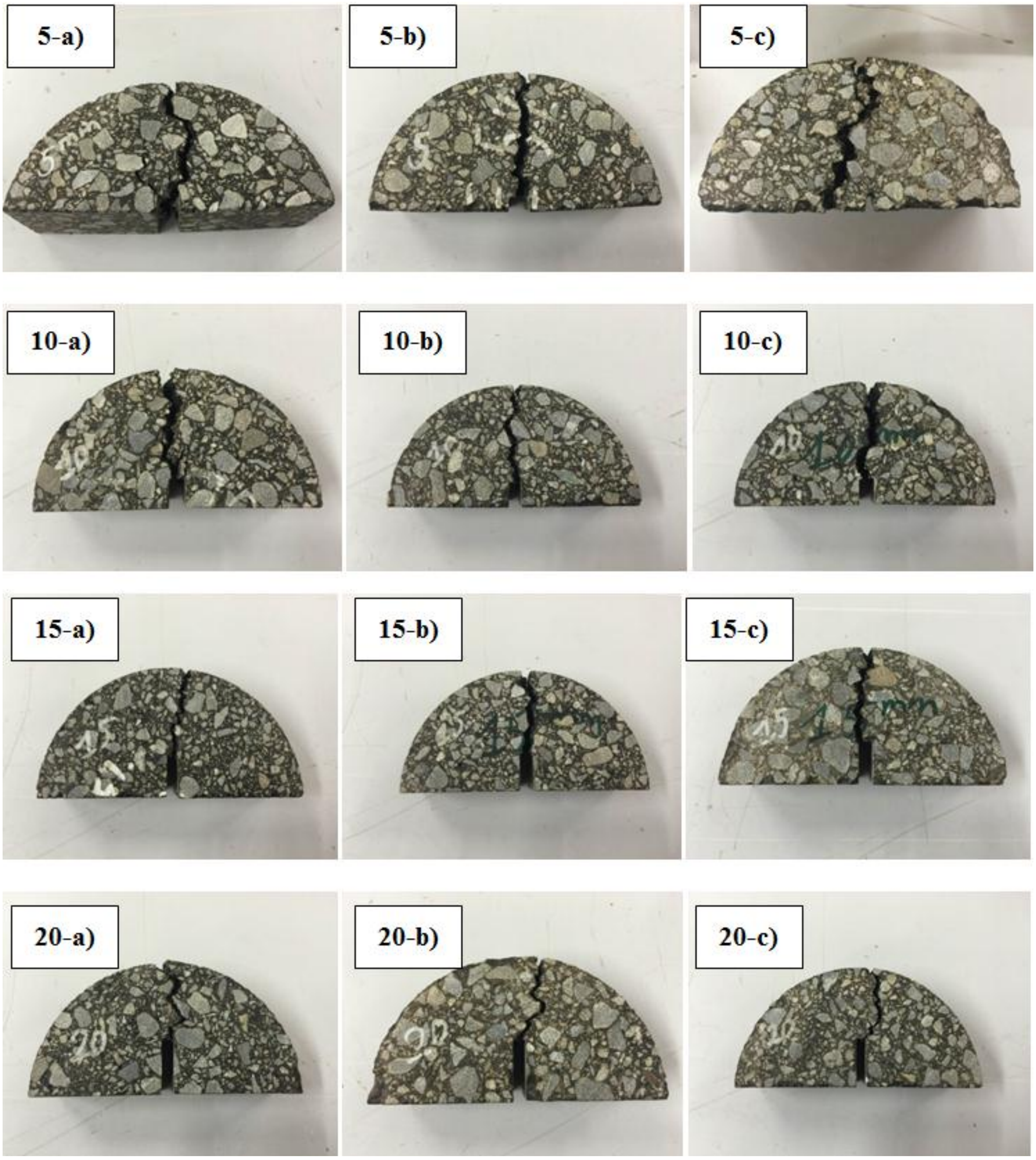

Figure 4.20 Typical SCB samples with 5, 10, 15, and 20 mm notch length after testing

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

This study consists of two major parts: the study of warm mix asphalt (WMA) incorporating high reclaimed asphalt pavement (RAP) content, and the evaluation of the semi-circular bending test as a potential test to characterize asphalt mix behaviour. For the first part, the laboratory tests were done at the Transportation Laboratory, University of Canterbury, to evaluate the performance of the WMA–RAP mixtures, which was then compared to that of hot mix asphalt (HMA) as a control mixture. The proportions of RAP added ranged from 0% to 70%, using one type of binder and two types of warm mix additives. In the second part, the investigation was studied the basic properties of asphalt mixtures, based on results obtained from the semi-circular bending test. The experiments were carried out on samples prepared with four different notch depths and two air void targets. Furthermore, the maximum stress of the semi-circular test was also compared with tensile strength from the indirect tensile strength test. Based on the results, conclusions have been drawn and recommendations made for the two parts, as below.

5.1 The study of warm mix asphalt incorporating high reclaimed asphalt pavement content.

1. Both Evotherm and Sylvaroad reduced the binder’s viscosity and the reduction increased with the increase of additive content. In producing samples for the mechanical performance tests, Evotherm was added into the binder at a percentage of 0.5% by mass of the binder while Sylvaroad was added at 2%. The addition of Sylvaroad showed a greater reduction in viscosity than did Evotherm.

2. Evotherm enhanced coating and adhesion between aggregate and binder in WMA-RAP mixtures. This greatly improved the moisture resistance of mixtures. Mixtures

with Evotherm showed much better moisture resistance than did HMA and the mixtures with Sylvaroad. WMA and WMA-25%RAP with Evotherm had tensile strength ratios, (TSR) larger than 80%, while WMA-Evotherm with 50% and 70% RAP showed TSR values greater than 70%. Sylvaroad showed a negligible effect on the moisture resistance of mixtures. HMA and all the mixtures with Sylvaroad failed the TSR value of 80% threshold, and considerable stripping was observed in these mixtures.

3. The combination of Sylvaroad and Evotherm considerably improved the moisture resistance of WMA-RAP mixtures. All of them had TSR values equal to or higher than 80%.

4. WMA additives not only reduced the binder’s viscosity but also softened the mixtures. WMA showed lower rutting resistance than HMA regardless of the additive type. The WMA with Sylvaroad had the greatest resistance to fatigue cracking, while HMA showed better fatigue resistance than WMA-Evotherm.

5. The addition of RAP stiffened the mixtures, improving the rutting resistance significantly, while reducing the fatigue resistance. This indicates that rutting is not a problem with WMA-RAP mixtures whereas fatigue still need more investigation and improvement. Sylvaroad mixtures showed better performance in fatigue resistance than Evotherm mixtures, while performing worse in rutting resistance.

6. The optimum binder contents in this study were reduced when more RAP in WMA was added. This affected the rutting, fatigue, and moisture resistance results considerably. The statement was shown conclusively via the extended cases, in which the binder contents in the WMA mixtures incorporating 50% and 70% RAP using

Evotherm were increased to be similar to the binder content of WMA-25%RAP. The WMA-50% and 70% RAP mixtures improved their moisture resistance, and significantly improved their fatigue resistance. The rutting resistance reduced with the increase in binder content, but was still substantially greater than that of WMA–25% RAP mixture and the control HMA.

7. In this study, the addition of 0.5% Evotherm may not be sufficient and it is recommended that it be increased. With increasing RAP content, it is concluded that increasing the mixing temperatures, the binder content, or additive amounts are necessary to improve the mixtures' performance. Further study on the increase of the Evotherm proportion when increasing the RAP content is recommended.

8. To maintain good fatigue resistance performance for mixtures with Evotherm, the maximum proportion of RAP into WMA is recommended to not exceed 50% by mass of the total mix if the binder is increased. For hot climates where rutting is the major failure type, while fatigue cracking is not a concern, the RAP portion can be increased to 70%.

9. For Sylvaroad mixtures, RAP proportion can be added up to 70% if the moisture resistance of the mixture is satisfied and if the binder content is increased to maintain good fatigue resistance. The moisture resistance issue of Sylvaroad mixtures can be improved by combining Evotherm into the mixtures, and therefore an RAP proportion of 70% is possible.

5.2 The study of the semi-circular bending test

1. The SCB test is applicable for 100 mm diameter samples produced for AC10 mixture. The test can also be used to achieve the tensile strength of asphalt mixture instead of using an indirect tensile strength test.

2. Notch lengths from 5–15 mm were found to be suitable for an SCB test using 100 mm diameter samples.

3. The thickness of 30 mm should be the minimum value used for the SCB test on 100 mm diameter samples.

4. Test samples with cracks that do not initiate from the notch tip and run to the loading strip, or have more than one major crack, should be eliminated and replaced by others.

5. The SCB test on 100 mm diameter samples can yield consistent and repeatable results for evaluating the fracture resistance of asphalt mixtures.

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APPENDIX 1: MOISTURE RESISTANCE

A1.1 Hot mix asphalt

Sample ID	Thickness (mm)	Diameter (mm)	Subset	Dry Mass (g)	SSD Mass (g)	Wet Mass (g)	Water temp. (°C)	Water density (g/cm^3)	Bulk. Sp.Gr. (g/cm^3)	Max Sp.Gr. (g/cm^3)	Air Void (%)	Ave. Air Void (%)	Max Load (N)	ITS (Dry) (kPa)
	T	D		A	B	C	WT	E	F	G	H	AAV	P	ITD
									A*E / (C-B)	G	(100*(G-F)/G)			2*1000 *P/πDT
3	85.56	149.50	Dry	3360.72	1894.94	3379.84	11.9	1	2.263	2.452	7.69		12984.90	646.3
4	84.74	149.50	Dry	3345.93	1892.77	3362.95	11.9	1	2.276	2.452	7.17	7.70	13137.01	660.2
5	85.77	149.50	Dry	3351.59	1889.93	3379.61	11.9	1	2.250	2.452	8.24		11955.70	593.6
2	85.00	149.50	Wet	3337.16	1867.87	3357.79	11.9	1	2.240	2.452	8.64		5455.79	
5	85.00	149.50	Wet	3358.82	1888.38	3371.19	11.9	1	2.265	2.452	7.61	8.12	6261.99	
7	85.00	149.50	Wet	3359.30	1887.29	3378.24	11.9	1	2.253	2.452	8.10		5650.75	
Average														**633.3**
Coefficient of variation (%)														**5.55**

Sample ID	Volume of specimen (cm^3)	Volume of air (cm^3)	Partial saturated mass (g)	Degree of Saturation (%)	Max Load (N)	ITS (Wet) (kPa)	Tensile strength ratio (%)
	I	J	K	SD	P	ITW	TSR
	(C - B) / E	H * I / 100		100 * (K - A) / J		2*1000*P/πDT	100* ITW / ITD
2	1489.92	128.80	3414.00	59.7	5455.79	273.3	
5	1482.81	112.86	3426.23	59.7	6261.99	313.7	
7	1490.95	120.80	3431.35	59.6	5650.75	283.1	**45.8**
Average						**290.0**	
Coefficient of Variation (%)						**7.27**	

A1.2 Warm mix asphalt with 0.5% Evotherm

Sample ID	Thickness (mm)	Diameter (mm)	Subset	Dry Mass (g)	SSD Mass (g)	Wet Mass (g)	Water temp. (°C)	Water density (g/cm^3)	Bulk. Sp.Gr. (g/cm^3)	Max Sp.Gr. (g/cm^3)	Air Void (%)	Ave. Air Void (%)	Max Load (N)	ITS (Dry) (kPa)
	T	D		A	B	C	WT	E	F	G	H	AAV	P	ITD
									A*E / (C-B)	G	(100*(G-F)/G)			2*1000 *P/πDT
1	84.85	149.50	Dry	3355.93	1902.04	3377.07	17.8	0.999	2.273	2.459	7.55		10858.35	545.0
4	85.24	149.50	Dry	3365.09	1898.61	3386.31	17.8	0.999	2.260	2.459	8.09	7.90	10790.06	539.0
6	85.13	149.50	Dry	3362.72	1896.67	3383.07	17.8	0.999	2.260	2.459	8.07		9948.78	497.6
2	85.06	149.50	Wet	3364.78	1893.90	3380.57	17.8	0.999	2.261	2.459	8.03		9404.94	
5	84.34	149.50	Wet	3355.69	1901.98	3377.60	17.8	0.999	2.272	2.459	7.59	7.66	9620.69	
7	84.42	149.50	Wet	3362.35	1910.14	3385.00	17.8	0.999	2.277	2.459	7.36		9661.70	
Average														**527.2**
Coefficient of variation (%)														**4.89**

Sample ID	Volume of specimen (cm^3)	Volume of air (cm^3)	Partial saturated mass (g)	Degree of Saturation (%)	Max Load (N)	ITS (Wet) (kPa)	Tensile strength ratio (%)
	I	J	K	SD	P	ITW	TSR
	(C - B) / E	H * I / 100		100 * (K - A) / J		2*1000*P/πDT	100* ITW / ITD
2	1488.16	119.53	3460.94	80.4	9404.94	470.9	
5	1477.10	112.17	3450.19	84.3	9620.69	485.8	
7	1476.34	108.70	3450.00	80.6	9661.70	487.3	**91.3**
Average						**481.3**	
Coefficient of Variation (%)						**1.89**	

A1.3 Warm mix asphalt + 25% RAP with 0.5% Evotherm

Sample ID	Thickness (mm)	Diameter (mm)	Subset	Dry Mass (g)	SSD Mass (g)	Wet Mass (g)	Water temp. (°C)	Water density (g/cm³)	Bulk. Sp.Gr. (g/cm³)	Max Sp.Gr. (g/cm³)	Air Void (%)	Ave. Air Void (%)	Max Load (N)	ITS (Dry) (kPa)
	T	D		A	B	C	WT	E	F	G	H	AAV	P	ITD
									A*E / (C-B)	G	(100*(G-F)/G)			2*1000 *P/πD T
1	85.20	149.50	Dry	3374.20	1907.40	3395.90	15.7	0.999	2.265	2.468	8.23		13868.88	693.2
2	84.15	149.50	Dry	3379.31	1920.53	3394.81	15.7	0.999	2.290	2.468	7.20	7.59	14540.64	735.9
6	84.35	149.50	Dry	3377.48	1918.22	3393.99	15.7	0.999	2.286	2.468	7.34		15073.29	761.0
3	84.85	149.50	Wet	3378.96	1914.07	3397.46	15.7	0.999	2.276	2.468	7.78		11169.31	
4	84.21	149.50	Wet	3375.87	1919.07	3394.40	15.7	0.999	2.286	2.468	7.36	7.70	12740.50	
5	85.24	149.50	Wet	3377.51	1920.09	3405.88	15.7	0.999	2.271	2.468	7.97		11883.49	
Average														**730.0**
Coefficient of variation (%)														**4.69**

Sample ID	Volume of specimen (cm³)	Volume of air (cm³)	Partial saturated mass (g)	Degree of Saturation (%)	Max Load (kN)	ITS (Wet) (kPa)	Tensile strength ratio (%)
	I	J	K	SD	P	ITW	TSR
	(C - B) / E	H * I / 100		100 * (K - A) / J		2*1000*P/πDT	100* ITW / ITD
3	1484.87	115.52	3473.10	81.5	11169.31	560.5	
4	1476.81	108.70	3451.93	70.0	12740.50	644.2	
5	1487.28	118.51	3467.42	75.9	11883.49	593.7	**82.1**
Average						**599.5**	
Coefficient of Variation (%)						**7.03**	

A1.4 Warm mix asphalt + 50% RAP with 0.5% Evotherm

Sample ID	Thickness (mm)	Diameter (mm)	Subset	Dry Mass (g)	SSD Mass (g)	Wet Mass (g)	Water temp. (°C)	Water density (g/cm^3)	Bulk. Sp.Gr. (g/cm^3)	Max Sp.Gr. (g/cm^3)	Air Void (%)	Ave. Air Void (%)	Max Load (kN)	ITS (Dry) (kPa)
	T	D		A	B	C	WT	E	F	G	H	AAV	P	ITD
									A*E / (C-B)	G	(100*(G-F)/G)			2*1000* P/πDT
1	84.21	149.50	Dry	3371.74	1908.01	3385.77	16.5	0.999	2.279	2.463	7.44		18623.32	941.7
2	85.10	149.50	Dry	3374.76	1906.53	3395.87	16.5	0.999	2.264	2.463	8.07	7.57	18767.02	939.1
5	84.22	149.50	Dry	3373.17	1922.55	3396.92	16.5	0.999	2.286	2.463	7.19		18994.39	960.4
3	84.35	149.50	Wet	3374.56	1914.42	3389.63	16.5	0.999	2.285	2.463	7.20		14608.28	
4	85.38	149.50	Wet	3375.16	1909.76	3397.88	16.5	0.999	2.266	2.463	7.99	7.72	12969.19	
6	85.48	149.50	Wet	3373.38	1910.06	3397.05	16.5	0.999	2.266	2.463	7.97		13499.15	
Average														**947.1**
Coefficient of variation (%)														**1.22**

Sample ID	Volume of specimen (cm^3)	Volume of air (cm^3)	Partial saturated mass (g)	Degree of Saturation (%)	Max Load (kN)	ITS (Wet) (kPa)	Tensile strength ratio (%)
	I	J	K	SD	P	ITW	TSR
	(C - B) / E	H * I / 100		100 * (K - A) / J		2*1000*P/πDT	100* ITW / ITD
3	1476.69	106.32	3455.80	76.4	14608.28	737.5	
4	1489.61	119.00	3465.96	76.3	12969.19	646.8	
6	1488.48	118.59	3451.25	65.7	13499.15	672.5	**72.4**
Average						**685.6**	
Coefficient of Variation (%)						**6.82**	

A1.5 Warm mix asphalt + 70% RAP with 0.5% Evotherm

Sample ID	Thickness (mm)	Diameter (mm)	Subset	Dry Mass (g)	SSD Mass (g)	Wet Mass (g)	Water temp. (°C)	Water density (g/cm^3)	Bulk. Sp.Gr. (g/cm^3)	Max Sp.Gr. (g/cm^3)	Air Void (%)	Ave. Air Void (%)	Max Load (N)	ITS (Dry) (kPa)
	T	D		A	B	C	WT	E	F	G	H	AAV	P	ITD
									A*E / (C-B)	G	(100*(G-F)/G)			2*1000 *P/πD T
1	85.64	149.50	Dry	3386.12	1914.33	3405.40	16.2	0.999	2.269	2.470	8.15	7.86	20318.96	1010.3
4	85.34	149.50	Dry	3385.80	1916.06	3406.68	16.2	0.999	2.269	2.470	8.13		19905.86	993.3
5	84.89	149.50	Dry	3386.75	1939.25	3416.78	16.2	0.999	2.290	2.470	7.29		19280.57	967.2
2	84.58	149.50	Wet	3388.80	1929.85	3409.98	16.2	0.999	2.287	2.470	7.40	7.77	15798.51	
3	85.38	149.50	Wet	3387.77	1921.76	3410.80	16.2	0.999	2.273	2.470	7.98		16022.87	
6	85.48	149.50	Wet	3388.12	1927.99	3416.37	16.2	0.999	2.274	2.470	7.93		14068.14	
Average														**990.3**
Coefficient of variation (%)														**2.19**

Sample ID	Volume of specimen (cm^3)	Volume of air (cm^3)	Partial saturated mass (g)	Degree of Saturation (%)	Max Load (kN)	ITS (Wet) (kPa)	Tensile strength ratio (%)
	I	J	K	SD	P	ITW	TSR
	(C - B) / E	H * I / 100		100 * (K - A) / J		2*1000*P/πDT	100* ITW / ITD
2	1481.61	109.62	3456.95	62.2	15798.51	795.4	**77.3**
3	1490.53	118.96	3468.83	68.1	16022.87	799.1	
6	1489.87	118.15	3478.00	76.1	14068.14	700.9	
Average						**765.1**	
Coefficient of Variation (%)						**7.28**	

A1.6 Warm mix asphalt + 50% RAP with 0.5% Evotherm (4.6% binder content - Extended case)

Sample ID	Thickness (mm)	Diameter (mm)	Subset	Dry Mass (g)	SSD Mass (g)	Wet Mass (g)	Water temp. (°C)	Water density (g/cm^3)	Bulk. Sp.Gr. (g/cm^3)	Max Sp.Gr. (g/cm^3)	Air Void (%)	Ave. Air Void (%)	Max Load (kN)	ITS (Dry) (kPa)
	T	D		A	B	C	WT	E	F	G	H	AAV	P	ITD
									A*E / (C-B)	G	(100*(G-F)/G)			2*1000 *P/πDT
4	84.59	149.50	Dry	3359.80	1908.21	3381.99	17	0.999	2.277	2.452	7.11		18017.75	907.0
5	85.16	149.50	Dry	3362.28	1900.09	3386.97	17	0.999	2.259	2.452	7.86	7.27	16023.1	801.2
6	84.51	149.50	Dry	3361.02	1914.04	3383.82	17	0.999	2.284	2.452	6.83		18527.13	933.6
1	85.22	149.50	Wet	3361.28	1899.58	3386.89	17	0.999	2.258	2.452	7.92		12922.67	
2	84.37	149.50	Wet	3357.11	1897.43	3370.44	17	0.999	2.277	2.452	7.14	7.58	14693.71	
3	85.45	149.50	Wet	3365.41	1907.60	3392.98	17	0.999	2.263	2.452	7.68		12293.22	
Average														**880.6**
Coefficient of variation (%)														**7.95**

Sample ID	Volume of specimen (cm^3)	Volume of air (cm^3)	Partial saturated mass (g)	Degree of Saturation (%)	Max Load (kN)	ITS (Wet) (kPa)	Tensile strength ratio (%)
	I	J	K	SD	P	ITW	TSR
	(C - B) / E	H * I / 100		100 * (K - A) / J		2*1000*P/πDT	100* ITW / ITD
1	1488.80	117.87	3441.16	67.8	12922.67	645.7	
2	1474.48	105.26	3438.65	77.5	14693.71	741.6	
3	1475.26	113.36	3444.02	74.3	12293.22	612.6	**75.7**
Average						**666.6**	
Coefficient of Variation (%)						**10.05**	

A1.7 Warm mix asphalt + 70% RAP with 0.5% Evotherm (4.6% binder content - Extended case)

Sample ID	Thickness (mm)	Diameter (mm)	Subset	Dry Mass (g)	SSD Mass (g)	Wet Mass (g)	Water temp. (°C)	Water density (g/cm^3)	Bulk. Sp.Gr. (g/cm^3)	Max Sp.Gr. (g/cm^3)	Air Void (%)	Ave. Air Void (%)	Max Load (N)	ITS (Dry) (kPa)
	T	D		A	B	C	WT	E	F	G	H	AAV	P	ITD
									A*E / (C-B)	G	(100*(G-F)/G)			2*1000*P/πDT
1	84.39	149.50	Dry	3366.10	1913.40	3386.28	13	0.999	2.283	2.456	7.03		18792.96	948.3
3	84.66	149.50	Dry	3369.70	1948.14	3414.26	13	0.999	2.296	2.456	6.50	7.06	16951.21	852.7
4	85.24	149.50	Dry	3362.92	1919.03	3400.75	13	0.999	2.267	2.456	7.67		17761.91	887.3
2	85.31	149.50	Wet	3361.55	1898.32	3383.85	13	0.999	2.261	2.456	7.94		15514.51	
5	84.91	149.50	Wet	3365.10	1920.82	3392.85	13	0.999	2.284	2.456	7.00	7.59	15132.49	
6	85.34	149.50	Wet	3361.46	1898.86	3382.63	13	0.999	2.263	2.456	7.84		14398.11	
Average														**896.1**
Coefficient of variation (%)														**5.40**

Sample ID	Volume of specimen (cm^3)	Volume of air (cm^3)	Partial saturated mass (g)	Degree of Saturation (%)	Max Load (kN)	ITS (Wet) (kPa)	Tensile strength ratio (%)
	I	J	K	SD	P	ITW	TSR
	(C - B) / E	H * I / 100		100 * (K - A) / J		2*1000*P/πDT	100* ITW / ITD
2	1487.02	118.11	3440.20	66.6	17761.91	886.6	
5	1483.20	103.83	3422.70	57.6	15132.49	759.0	
6	1485.26	116.39	3437.99	65.8	14398.11	718.4	**87.9**
Average						**788.0**	
Coefficient of Variation (%)						**11.14**	

A1.8 Warm mix asphalt with 2% Sylvaroad

Sample ID	Thickness (mm)	Diameter (mm)	Subset	Dry Mass (g)	SSD Mass (g)	Wet Mass (g)	Water temp. (°C)	Water density (g/cm^3)	Bulk. Sp.Gr. (g/cm^3)	Max Sp.Gr. (g/cm^3)	Air Void (%)	Ave. Air Void (%)	Max Load (N)	ITS (Dry) (kPa)
	T	D		A	B	C	WT	E	F	G	H	AAV	P	ITD
									A*E / (C-B)	G	(100*(G-F)/G)			2*1000 *P/πDT
2	85.13	149.50	Dry	3368.18	1905.07	3390.47	15.7	0.999	2.276	2.459	7.41		8534.15	426.9
3	85.02	149.50	Dry	3359.07	1884.55	3371.64	13.7	0.999	2.268	2.459	7.75	7.82	7909.89	396.2
5	85.32	149.50	Dry	3361.42	1890.97	3380.39	15.5	0.999	2.255	2.459	8.29		8317.09	415.1
7	85.65	150.71	Wet	3352.52	1887.17	3373.72	17.4	0.999	2.253	2.459	8.36			
8	85.12	151.75	Wet	3363.62	1899.45	3384.6	17.4	0.999	2.263	2.459	7.97	8.20		
9	85.45	150.98	Wet	3365.68	1893.01	3384.05	17.4	0.999	2.255	2.459	8.28			
Average														**412.7**
Coefficient of variation (%)														**3.76**

Sample ID	Volume of specimen (cm^3)	Volume of air (cm^3)	Partial saturated mass (g)	Degree of Saturation (%)	Max Load (kN)	ITS (Wet) (kPa)	Tensile strength ratio (%)
	I	J	K	SD	P	ITW	TSR
	(C - B) / E	H * I / 100		100 * (K - A) / J		2*1000*P/πDT	100* ITW / ITD
7	1488.04	124.40	3426.61	59.6	3103.52	153.1	
8	1486.64	118.48	3439.43	64.0	2859.18	140.9	
9	1492.53	123.54	3447.80	66.5	3032.18	149.6	**35.8**
Average						**147.9**	
Coefficient of variation (%)						**4.23**	

A1.9 Warm mix asphalt + 25% RAP with 2% Sylvaroad

Sample ID	Thickness (mm)	Diameter (mm)	Subset	Dry Mass (g)	SSD Mass (g)	Wet Mass (g)	Water temp. (°C)	Water density (g/cm^3)	Bulk. Sp.Gr. (g/cm^3)	Max Sp.Gr. (g/cm^3)	Air Void (%)	Ave. Air Void (%)	Max Load (N)	ITS (Dry) (kPa)
	T	D		A	B	C	WT	E	F	G	H	AAV	P	ITD
									A*E / (C-B)	G	(100*(G-F)/G)			2*1000 *P/πDT
2	85.33	149.50	Dry	3384.41	1921.72	3405.12	15.7	0.999	2.279	2.468	7.63	7.82	12105.02	604.1
3	85.40	149.50	Dry	3383.27	1923.39	3408.25	15.7	0.999	2.276	2.468	7.75		10471.91	522.2
7	85.24	149.50	Dry	3376.35	1901.60	3388.78	18	0.999	2.268	2.468	8.09		10782.54	538.7
1	85.65	150.00	Wet	3381.81	1929.55	3415.65	15.7	0.999	2.273	2.468	7.87	7.82		
4	85.73	149.91	Wet	3379.66	1926.75	3413.78	15.7	0.999	2.270	2.468	7.99			
5	85.29	149.71	Wet	3384.03	1915.90	3398.92	13.7	0.999	2.280	2.468	7.62			
Average														**555.0**
Coefficient of variation (%)														**7.81**

Sample ID	Volume of specimen (cm^3)	Volume of air (cm^3)	Partial saturated mass (g)	Degree of Saturation (%)	Max Load (kN)	ITS (Wet) (kPa)	Tensile strength ratio (%)
	I	J	K	SD	P	ITW	TSR
	(C - B) / E	H * I / 100		100 * (K - A) / J		2*1000*P/πDT	100* ITW / ITD
1	1487.59	117.07	3460.85	67.5	6374.59	315.9	**57.5**
4	1488.52	118.88	3452.25	61.1	6492.56	321.6	
5	1484.50	113.09	3457.10	64.6	6400.90	319.1	
Average						**318.9**	
Coefficient of variation (%)						**0.90**	

A1.10 Warm mix asphalt + 50% RAP with 2% Sylvaroad

Sample ID	Thickness (mm)	Diameter (mm)	Subset	Dry Mass (g)	SSD Mass (g)	Wet Mass (g)	Water temp. (°C)	Water density (g/cm^3)	Bulk. Sp.Gr. (g/cm^3)	Max Sp.Gr. (g/cm^3)	Air Void (%)	Ave. Air Void (%)	Max Load (N)	ITS (Dry) (kPa)
	T	D		A	B	C	WT	E	F	G	H	AAV	P	ITD
									A*E / (C-B)	G	(100*(G-F)/G)			2*1000 *P/πDT
2	85.47	149.50	Dry	3377.62	1902.13	3392.16	13.7	0.999	2.265	2.463	8.04	7.78	16356.87	814.9
3	85.59	149.50	Dry	3374.48	1915.04	3398.83	15.3	0.999	2.272	2.463	7.74		13901.85	691.7
4	85.25	149.50	Dry	3378.79	1914.55	3397.20	15.3	0.999	2.277	2.463	7.55		15888.56	793.6
1	85.29	150.03	Wet	3378.89	1909.35	3394.19	13.7	0.999	2.273	2.463	7.68	7.78		
5	85.52	150.15	Wet	3374.50	1913.40	3398.42	15.3	0.999	2.270	2.463	7.81			
6	85.33	149.96	Wet	3375.72	1903.25	3389.50	15.3	0.999	2.269	2.463	7.86			
Average														**766.7**
Coefficient of variation (%)														**8.59**

Sample ID	Volume of specimen (cm^3)	Volume of air (cm^3)	Partial saturated mass (g)	Degree of Saturation (%)	Max Load (kN)	ITS (Wet) (kPa)	Tensile strength ratio (%)
	I	J	K	SD	P	ITW	TSR
	(C - B) / E	H * I / 100		100 * (K - A) / J		2*1000*P/πDT	100* ITW / ITD
1	1486.33	114.20	3445.84	58.6	9443.10	469.8	**56.0**
5	1486.51	116.16	3459.80	73.4	8003.38	396.8	
6	1487.74	116.90	3453.69	66.7	8495.58	422.6	
Average						**429.7**	
Coefficient of variation (%)						**8.61**	

A1.11 Warm mix asphalt + 70% RAP with 2% Sylvaroad

Sample ID	Thickness (mm)	Diameter (mm)	Subset	Dry Mass (g)	SSD Mass (g)	Wet Mass (g)	Water temp. (°C)	Water density (g/cm^3)	Bulk. Sp.Gr. (g/cm^3)	Max Sp.Gr. (g/cm^3)	Air Void (%)	Ave. Air Void (%)	Max Load (N)	ITS (Dry) (N/cm2)
	T	D		A	B	C	WT	E	F	G	H	AAV	P	ITD
									A*E / (C-B)	G	(100*(G-F)/G)			2*1000* P/πDT
1	84.92	149.50	Dry	3382.86	1912.79	3397.62	16.6	0.999	2.276	2.470	7.85		15271.18	765.8
2	85.18	149.50	Dry	3388.26	1921.70	3408.06	16.6	0.999	2.277	2.470	7.80	7.81	15672.90	783.5
3	84.91	149.50	Dry	3383.93	1916.08	3400.20	16.6	0.999	2.278	2.470	7.78		15314.27	768.0
4	85.45	150.40	Wet	3393.75	1917.26	3409.91	16.6	0.999	2.271	2.470	8.04			
5	85.16	150.07	Wet	3391.00	1933.93	3415.32	17.4	0.999	2.287	2.470	7.42	7.78		
6	85.49	150.34	Wet	3383.21	1928.07	3413.52	17.4	0.999	2.275	2.470	7.88			
Average														**772.4**
Coefficient of variation (%)														**1.25**

Sample ID	Volume of specimen (cm^3)	Volume of air (cm^3)	Partial saturated mass (g)	Degree of Saturation (%)	Max Load (kN)	ITS (Wet) (kPa)	Tensile strength ratio (%)
	I	J	K	SD	P	ITW	TSR
	(C - B) / E	H * I / 100		100 * (K - A) / J		2*1000*P/πDT	100* ITW / ITD
4	1494.14	120.15	3478.65	70.7	9775.59	484.3	
5	1482.87	109.99	3469.20	71.1	11047.00	550.3	
6	1486.94	117.21	3468.78	73.0	10510.18	520.6	**67.1**
Average						**518.4**	
Coefficient of variation (%)						**6.38**	

A1.12 Warm mix asphalt + 0.5% Evotherm with 1% Sylvaroad

Sample ID	Thickness (mm)	Diameter (mm)	Subset	Dry Mass (g)	SSD Mass (g)	Wet Mass (g)	Water temp. (°C)	Water density (g/cm^3)	Bulk. Sp.Gr. (g/cm^3)	Max Sp.Gr. (g/cm^3)	Air Void (%)	Ave. Air Void (%)	Max Load (N)	ITS (Dry) (kPa)
	T	D		A	B	C	WT	E	F	G	H	AAV	P	ITD
									A*E / (C-B)	G	(100*(G-F)/G)			2*1000 *P/πDT
1	85.35	149.50	Dry	3364.08	1884.38	3375.6	17.6	0.999	2.254	2.459	8.33	7.99	10096.61	503.7
4	85.00	149.50	Dry	3370.34	1893.45	3378.61	17.6	0.999	2.267	2.459	7.79		10984.88	550.3
2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A			
3	85.42	149.75	WET	3370.44	1892.36	3381.81	17.6	0.999	2.261	2.459	8.05	7.96		
5	85.00	149.50	WET	3358	1893.99	3374.48	17	0.999	2.266	2.459	7.83			
6	85.00	150.00	WET	3374.93	1898.07	3388.64	17	0.999	2.262	2.459	8.00			
Average														**527.0**
Coefficient of variation (%)														**6.25**

Sample ID	Volume of specimen (cm^3)	Volume of air (cm^3)	Partial saturated mass (g)	Degree of Saturation (%)	Max Load (kN)	ITS (Wet) (kPa)	Tensile strength ratio (%)
	I	J	K	SD	P	ITW	TSR
	(C - B) / E	H * I / 100		100 * (K - A) / J		2*1000*P/πDT	100* ITW / ITD
3	1490.94	120.01	3443.05	60.5	8766.39	436.3	**82.8**
5	1481.97	116.10	3445.13	75.0	8382.90	420.0	
6	1492.06	119.30	3440.55	55.0	9061.58	452.5	
Average						**436.2**	
Coefficient of variation (%)						**3.72**	

A1.13 Warm mix asphalt + 25% RAP with 0.5% Evotherm and 1% Sylvaroad

Sample ID	Thickness (mm)	Diameter (mm)	Subset	Dry Mass (g)	SSD Mass (g)	Wet Mass (g)	Water temp. (°C)	Water density (g/cm^3)	Bulk. Sp.Gr. (g/cm^3)	Max Sp.Gr. (g/cm^3)	Air Void (%)	Ave. Air Void (%)	Max Load (N)	ITS (Dry) (kPa)
	T	D		A	B	C	WT	E	F	G	H	AAV	P	ITD
									A*E / (C-B)	G	(100*(G-F)/G)			2*1000*P/πDT
1	85.22	149.50	Dry	3385.51	1915.00	3399.60	17.6	0.999	2.278	2.468	7.68		13387.74	669.0
4	85.33	149.50	Dry	3387.07	1907.67	3392.65	16.4	0.999	2.279	2.468	7.66	7.84	13646.20	681.0
6	85.46	149.50	Dry	3385.49	1904.42	3397.20	16.4	0.999	2.266	2.468	8.18		14342.46	714.6
2	85.41	149.88	Wet	3385.26	1909.70	3398.44	17.6	0.999	2.272	2.468	7.94			
3	85.22	149.98	Wet	3383.51	1909.35	3397.04	16.4	0.999	2.272	2.468	7.92	7.92		
5	85.31	149.92	Wet	3384.28	1918.52	3406.15	16.4	0.999	2.273	2.468	7.90			
Average														**688.2**
Coefficient of variation (%)														**1.23**

Sample ID	Volume of specimen (cm^3)	Volume of air (cm^3)	Partial saturated mass (g)	Degree of Saturation (%)	Max Load (kN)	ITS (Wet) (kPa)	Tensile strength ratio (%)
	I	J	K	SD	P	ITW	TSR
	(C - B) / E	H * I / 100		100 * (K - A) / J		2*1000*P/πDT	100* ITW / ITD
2	1490.23	118.32	3455.90	59.7	12080.67	600.8	
3	1489.18	117.98	3454.04	59.8	12594.29	627.3	
5	1489.12	117.61	3466.61	70.0	11532.21	574.0	**87.3**
Average						**600.7**	
Coefficient of variation (%)						**4.44**	

A1.14 Warm mix asphalt + 50% RAP with 0.5% Evotherm and 1% Sylvaroad

Sample ID	Thickness (mm)	Diameter (mm)	Subset	Dry Mass (g)	SSD Mass (g)	Wet Mass (g)	Water temp. (°C)	Water density (g/cm^3)	Bulk. Sp.Gr. (g/cm^3)	Max Sp.Gr. (g/cm^3)	Air Void (%)	Ave. Air Void (%)	Max Load (N)	ITS (Dry) (kPa)
	T	D		A	B	C	WT	E	F	G	H	AAV	P	ITD
									A*E / (C-B)	G	(100*(G-F)/G)			2*1000 *P/πD T
1	85.15	149.50	Dry	3378.20	1908.05	3393.50	16.4	0.999	2.272	2.463	7.74		18213.53	910.9
3	85.10	149.50	Dry	3374.36	1910.22	3391.90	16.4	0.999	2.275	2.463	7.61	7.86	18590.75	930.3
6	85.32	149.50	Dry	3374.11	1895.90	3387.53	16.4	0.999	2.260	2.463	8.23		16113.26	804.2
2	85.20	149.95	Wet	3379.72	1907.90	3393.70	16.4	0.999	2.272	2.463	7.72			
4	85.41	150.11	Wet	3377.21	1901.76	3390.72	16.4	0.999	2.266	2.463	7.98	7.87		
5	85.02	150.11	Wet	3371.12	1899.22	3384.30	16.4	0.999	2.268	2.463	7.91			
Average														**881.8**
Coefficient of variation (%)														**1.56**

Sample ID	Volume of specimen (cm^3)	Volume of air (cm^3)	Partial saturated mass (g)	Degree of Saturation (%)	Max Load (kN)	ITS (Wet) (kPa)	Tensile strength ratio (%)
	I	J	K	SD	P	ITW	TSR
	(C - B) / E	H * I / 100		100 * (K - A) / J		2*1000*P/πDT	100* ITW / ITD
2	1487.29	114.82	3448.16	59.6	14469.18	721.0	
4	1490.45	119.00	3463.71	72.7	14441.14	717.1	
5	1486.57	117.59	3461.43	76.8	13498.58	673.3	**79.8**
Average						**703.8**	
Coefficient of variation (%)						**3.76**	

A1.15 Warm mix asphalt + 70% RAP with 0.5% Evotherm and 1% Sylvaroad

Sample ID	Thickness (mm)	Diameter (mm)	Subset	Dry Mass (g)	SSD Mass (g)	Wet Mass (g)	Water temp. (°C)	Water density (g/cm^3)	Bulk. Sp.Gr. (g/cm^3)	Max Sp.Gr. (g/cm^3)	Air Void (%)	Ave. Air Void (%)	Max Load (N)	ITS (Dry) (kPa)
	T	D		A	B	C	WT	E	F	G	H	AAV	P	ITD
									A*E / (C-B)	G	(100*(G-F)/G)			2*1000 *P/πD T
1	85.11	149.50	Dry	3390.30	1920.25	3403.70	17.4	0.999	2.283	2.470	7.56		21735.91	1087.5
3	85.32	149.50	Dry	3388.66	1906.01	3395.85	17.4	0.999	2.272	2.470	8.01	7.79	21494.73	1072.9
2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A			N/A
4	85.04	149.77	Wet	3387.02	1913.40	3397.63	17.4	0.999	2.280	2.470	7.70			
5	84.98	149.88	Wet	3386.85	1912.43	3395.10	17.4	0.999	2.282	2.470	7.61	7.66		
6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A			
Average														**1080.2**
Coefficient of variation (%)														**0.96**

Sample ID	Volume of specimen (cm^3)	Volume of air (cm^3)	Partial saturated mass (g)	Degree of Saturation (%)	Max Load (kN)	ITS (Wet) (kPa)	Tensile strength ratio (%)
	I	J	K	SD	P	ITW	TSR
	(C - B) / E	H * I / 100		100 * (K - A) / J		2*1000*P/πDT	100* ITW / ITD
4	1485.72	114.44	3463.41	66.7	17358.33	867.6	
5	1484.15	112.95	3458.44	63.4	17543.58	876.8	
6	N/A	N/A	N/A	N/A	N/A	N/A	**80.7**
Average						**872.2**	
Coefficient of variation (%)						**0.75**	

APPENDIX 2: FATIGUE RESISTANCE

A2.1 Volumetric properties

a) HMA, WMA and WMA-RAP mixtures with Evotherm

Type of mix	ID	m1_mass in air (g)	m2_mass in water (g)	m3_mass of saturated sample (g)	Water temp. (°C)	Density of water (g/cm^3)	Bulk density G_{mb} (g/cm^3)	Maximum density G_{mm} (g/cm^3)	Air void (%)
HMA	13	3105.9	1750.7	3109.6	14.4	0.999	2.283	2.452	6.87
	15	2983.4	1684.9	2986.5	12.6	1	2.292	2.452	6.51
	16	2957.8	1662.3	2961.3	14.4	0.999	2.275	2.452	7.23
WMA-E	3	2969.8	1673.4	2974.0	14.8	0.999	2.281	2.459	7.22
	5	2964.9	1664.9	2968.6	12.6	1	2.274	2.459	7.49
	8	2969.8	1667.6	2974.0	13.9	0.999	2.271	2.459	7.62
25R-E	5	2992.6	1686.8	2998.4	13.9	0.999	2.279	2.468	7.62
	6	2975.2	1681.6	2979.5	13.9	0.999	2.290	2.468	7.20
	7	2946.2	1663.5	2951.2	13.9	0.999	2.286	2.468	7.37
	8	2991.4	1692.1	2997.5	13.9	0.999	2.289	2.468	7.22
50R-E	1	2922.96	1643.43	2928.69	14.4	0.999	2.272	2.463	7.74
	3	2965.87	1676.65	2970	14.4	0.999	2.291	2.463	6.97
	4	2933.87	1646.07	2938	14.4	0.999	2.269	2.463	7.87
70R-E	5	2977.8	1690.03	2984.27	13.9	0.999	2.299	2.470	6.94
	6	2979.12	1696.43	2985.8	13.9	0.999	2.308	2.470	6.55
	7	2985.45	1696.99	2992.5	13.9	0.999	2.302	2.470	6.79
	8	2924.25	1658.2	2933.2	13.9	0.999	2.291	2.470	7.24
50R-E - 4.6% binder	1	2889.05	1642.57	2892.6	19.7	0.998	2.307	2.452	5.92
	2	2912.72	1662.44	2916.75	19.7	0.998	2.318	2.452	5.48
	3	2951.74	1680	2955	19.7	0.998	2.310	2.452	5.77
	4	2936.36	1672.08	2941.3	19.7	0.998	2.309	2.452	5.83
70R-E - 4.6% binder	1	2878.4	1634.7	2888	19.7	0.998	2.292	2.456	6.66
	2	2924.5	1671.13	2932.8	19.7	0.998	2.313	2.456	5.80
	3	2933.05	1672.7	2941.4	19.7	0.998	2.307	2.456	6.04
	4	2901.88	1650.4	2911.1	19.7	0.998	2.297	2.456	6.45

b) WMA and WMA-RAP mixtures with Sylvaroad

Type of mix	ID	m1_mass in air (g)	m2_mass in water (g)	m3_mass of saturated sample (g)	Water temp. (°C)	Density of water (g/cm³)	Bulk density G_{mb} (g/cm³)	Maximum density G_{mm} (g/cm³)	Air void (%)
WMA -S	1	2982.33	1696.09	2986.90	16.7	0.999	2.308	2.459	6.12
	2	2987.50	1698.61	2990.80	16.7	0.999	2.310	2.459	6.05
	3	3004.54	1705.61	3007.65	16.7	0.999	2.305	2.459	6.23
	4	2955.64	1681.05	2960.00	16.7	0.999	2.309	2.459	6.09
25R-S	1	2947.45	1669.04	2952.85	15.0	0.999	2.294	2.468	7.05
	2	2945.15	1672.57	2953.80	17.0	0.999	2.296	2.468	6.94
	3	2953.22	1678.51	2961.50	17.0	0.999	2.300	2.468	6.81
	4	2983.63	1694.99	2993.12	17.0	0.999	2.296	2.468	6.95
50R-S	1	2932.81	1656.49	2939.50	15.3	0.999	2.284	2.463	7.27
	2	2882.69	1628.37	2888.18	15.3	0.999	2.286	2.463	7.17
	3	2880.46	1627.33	2886.55	15.3	0.999	2.285	2.463	7.20
	4	2858.41	1610.08	2865.85	15.3	0.999	2.274	2.463	7.66
70R-S	1	2920.30	1667.69	2929.35	15.3	0.999	2.312	2.470	6.38
	2	2927.40	1676.93	2932.30	15.3	0.999	2.330	2.470	5.68
	3	2931.00	1678.17	2944.26	15.3	0.999	2.313	2.470	6.37
	4	2951.47	1685.37	2960.61	15.3	0.999	2.312	2.470	6.39

A2.2 Test results

a) HMA, WMA and WMA-RAP mixtures with Evotherm

Type of mix	ID	Initial stiffness (Mpa)	Average (Mpa)	Standard deviation	CoV (%)	Fatigue life	Average	Standard deviation	CoV (%)
HMA	13	3215	3282	123.9	3.8	527360	580013	46494	8.0
	15	3425				597260			
	16	3206				615420			
WMA-E	3	2949	3107	136.7	4.4	188220	205107	26118	12.7
	5	3192				191910			
	8	3179				235190			
25R-E	5	3681	3994	293.3	7.3	128130	108353	21851	20.2
	6	3808				77590			
	7	4216				109690			
	8	4270				118000			
50R-E	1	4794	4824	305.6	6.3	23070	24403	1574	6.5
	3	5144				26140			
	4	4535				24000			
70R-E	5	7070	7294	313.4	4.3	27580	24585	5478	22.3
	6	7740				16390			
	7	7283				27620			
	8	7081				26750			
50R-E - 4.6% binder	1	6159	6324	258.6	4.1	131210	102477	31169	30.4
	3	6622				69340			
	4	6191				106880			
70R-E - 4.6% binder	1	6583	6822	263.2	3.9	50380	65883	18024	27.4
	3	7104				61610			
	4	6777				85660			

b) WMA and WMA-RAP mixtures with Sylvaroad

Type of mix	ID	Initial stiffness (Mpa)	Average (Mpa)	Standard deviation	CoV (%)	Fatigue life	Average	Standard deviation	CoV (%)
WMA-S	1	2499	2527	34.8	1.4	845830	881920	310552	35.2
	2	2516				590990			
	4	2566				1208940			
25R-S	1	3081	3093	181.2	5.9	324380	349678	38505	11.0
	2	3310				320460			
	3	3112				349840			
	4	2868				404030			
50R-S	1	4002	4032	54.7	1.4	55750	76300	16970	22.2
	2	4109				69050			
	3	3986				91360			
	4	4030				89040			
70R-S	1	4923	5144	255.2	5.0	115150	95067	20993	22.1
	3	5423				96780			
	4	5085				73270			

APPENDIX 3: DYNAMIC MODULUS

A3.1 Volumetric properties

a) HMA, WMA and WMA-RAP mixtures with Evotherm

Mixture type	ID	m1_mass in air (g)	m2_mass in water (g)	m3_mass of saturated sample (g)	Water temp. (°C)	Density of water (g/cm^3)	Bulk density G_{mb} (g/cm^3)	Maximum density G_{mm} (g/cm^3)	Air void (%)
HMA	2	2666.55	1516.84	2668.87	11	1	2.315	2.452	5.59
	3	2684.22	1534.15	2686.49	11	1	2.329	2.452	4.99
	4	2678.37	1527.31	2680.71	11	1	2.322	2.452	5.29
WMA - E	1	2682.02	1533.58	2685.23	10	1	2.329	2.459	5.27
	2	2697.29	1547.52	2699.79	10	1	2.341	2.459	4.79
	3	2690.03	1542.03	2693.66	10	1	2.336	2.459	4.99
25R - E	1	2720.61	1570.63	2722.99	10	1	2.361	2.468	4.32
	2	2701.3	1554.12	2705.59	10	1	2.346	2.468	4.93
	4	2701.01	1550.18	2703.06	11.7	1	2.343	2.468	5.05
50R - E	3	2717.06	1567.26	2720.81	12.7	1	2.355	2.463	4.35
	4	2694.33	1552.3	2704.9	13.6	0.999	2.335	2.463	5.17
	5	2701.34	1556.67	2708.43	13.6	0.999	2.343	2.463	4.85
70R-E	2	2727.06	1584.65	2734.65	13.7	0.999	2.369	2.470	4.09
	3	2706.16	1568.56	2715.46	13.7	0.999	2.357	2.470	4.57
	4	2696.38	1553.07	2706.55	11.7	1	2.338	2.470	5.36

b) WMA and WMA-RAP mixtures with Sylvaroad

	ID	m1_mass in air (g)	m2_mass in water (g)	m3_mass of saturated sample (g)	Water temp. (°C)	Density of water (g/cm^3)	Bulk density G_{mb} (g/cm^3)	Maximum density G_{mm} (g/cm^3)	Air void (%)
WMA-S	1	2678.4	1528.5	2680.61	15.3	0.999	2.322	2.459	5.53
	2	2689.35	1537.19	2690.75	15.3	0.999	2.329	2.459	5.27
	3	2680.95	1529.47	2683.05	15.3	0.999	2.322	2.459	5.56
25R-S	1	2682.19	1533.7	2686.35	15.3	0.999	2.325	2.468	5.79
	2	2698.27	1547.27	2701.5	15.3	0.999	2.335	2.468	5.36
	3	2686.7	1536.74	2690.15	15.3	0.999	2.327	2.468	5.69
50R-S	1	2685.19	1537.4	2690.51	15.3	0.999	2.326	2.463	5.53
	2	2682.44	1534.71	2685.33	15.3	0.999	2.329	2.463	5.42
	3	2699.64	1551.6	2704.84	15.3	0.999	2.339	2.463	5.03
70R-S	1	2661.3	1521.09	2673.65	15.3	0.999	2.307	2.470	6.61
	2	2702.46	1557.42	2709.1	15.3	0.999	2.344	2.470	5.09
	3	2661.12	1521.58	2666.19	17.6	0.999	2.323	2.470	5.97

A3.2 Test results

a) Hot mix asphalt

Test Temperature	Frequency	Sample 2		Sample 3		Sample 4		Average Modulus MPa	Modulus CoV (%)	Average Phase Angle Degree	Phase Angle CoV (%)
Degree Celsius	Hz	Modulus MPa	Phase Angle Degree	Modulus MPa	Phase Angle Degree	Modulus MPa	Phase Angle Degree				
4.4	10	13639	17.69	15804	21.31	16308	18.27	15250	9.3	21.14	9.2
	5	12371	17.16	13441	21.93	14116	17.74	13309	6.6	20.42	12.7
	1	9150	20.32	9369	23.66	10162	20.77	9560	5.6	22.32	8.1
	0.5	7903	22.07	8104	25.15	8668	22.20	8225	4.8	23.85	7.3
	0.1	5349	26.86	5394	29.64	5868	26.43	5537	5.2	28.37	6.1
21.1	10	4419	32.03	4380	33.04	5156	29.98	4652	9.4	32.76	4.8
	5	3482	32.89	3518	34.41	4122	30.58	3707	9.7	33.55	5.7
	1	1908	36.52	1911	38.23	2366	33.98	2062	12.8	37.00	5.8
	0.5	1433	37.06	1458	38.72	1846	34.45	1579	14.7	37.24	5.8
	0.1	717	37.49	741	38.71	982	34.47	813	18.0	37.17	5.9
37.8	10	876	36.68	945	37.58	981	37.16	934	5.7	38.08	1.2
	5	642	34.78	691	35.50	722	34.67	685	5.8	35.91	1.3
	1	341	29.86	367	30.08	389	29.34	366	6.5	30.93	1.2
	0.5	277	26.72	300	27.20	313	26.53	297	6.2	28.32	1.2
	0.1	201	20.25	231	19.11	227	19.62	220	7.4	22.17	2.6
50	10	322	32.01	346	32.99	411	29.66	360	12.8	34.32	5.0
	5	224	30.58	265	28.93	293	25.93	261	13.4	31.26	7.5
	1	127	21.05	190	22.67	203	20.83	173	23.4	25.46	4.0
	0.5	111	16.71	160	18.32	171	17.95	147	21.8	22.84	3.7
	0.1	97	11.27	145	14.76	149	14.13	131	22.0	19.26	9.7

b) Warm mix asphalt with Evotherm

Test Temperature	Frequency	Sample 1		Sample 2		Sample 3		Average Modulus MPa	Modulus CoV (%)	Average Phase Angle Degree	Phase Angle CoV (%)
Degree Celsius	Hz	Modulus MPa	Phase Angle Degree	Modulus MPa	Phase Angle Degree	Modulus MPa	Phase Angle Degree				
4.4	10	12882	23.67	14840	18.49	16478	25.43	14733	12.2	23	16.0
	5	11636	22.15	13210	18.36	13553	26.78	12800	8.0	22	18.8
	1	8386	24.04	9857	21.89	10185	31.42	9476	10.1	26	19.4
	0.5	7176	25.71	8331	23.84	8663	32.95	8056	9.7	28	17.5
	0.1	4743	30.80	5575	29.11	5563	36.82	5294	9.0	32	12.6
21.1	10	4057	32.72	5279	38.17	5128	36.34	4821	13.8	36	7.8
	5	3262	34.06	4182	39.09	4052	36.93	3832	13.0	37	6.9
	1	1748	37.23	2255	41.62	2262	40.16	2088	14.1	40	5.6
	0.5	1321	37.47	1739	41.56	1717	39.91	1592	14.8	40	5.2
	0.1	688	35.82	938	40.74	910	37.07	846	16.2	38	6.8
37.8	10	741	36.74	1106	41.32	752	41.80	866	24.0	40	7.0
	5	532	34.55	854	38.04	560	40.64	649	27.5	38	8.1
	1	301	28.36	463	34.12	319	34.16	361	24.6	32	10.4
	0.5	250	24.85	365	31.60	261	31.30	292	21.8	29	13.0
	0.1	198	18.72	288	25.76	197	24.35	228	23.0	23	16.2
50	10	318	28.26	389	35.66	405	34.56	370	12.5	33	12.2
	5	222	25.00	285	30.44	260	31.36	256	12.4	29	11.9
	1	153	18.89	179	25.48	153	27.87	162	9.1	24	19.3
	0.5	136	15.10	135	20.31	117	25.01	129	8.4	20	24.6
	0.1	119	12.26	112	17.59	100	18.04	111	8.6	16	20.1

c) Warm mix asphalt + 25% RAP with Evotherm

Test Temperature	Frequency	Sample 1		Sample 2		Sample 4		Average Modulus MPa	Modulus CoV (%)	Average Phase Angle Degree	Phase Angle CoV (%)
Degree Celsius	Hz	Modulus MPa	Phase Angle Degree	Modulus MPa	Phase Angle Degree	Modulus MPa	Phase Angle Degree				
4.4	10	17973	15.26	19095	23.78	19457	21.49	18842	4.1	20.18	21.9
	5	16454	15.27	16123	23.76	15640	20.66	16072	2.5	19.90	21.6
	1	12273	17.28	11134	24.75	11055	22.15	11487	5.9	21.39	17.7
	0.5	10803	18.86	9625	26.85	9660	23.87	10029	6.7	23.19	17.4
	0.1	7758	23.08	6648	30.67	6780	28.07	7062	8.6	27.27	14.1
21.1	10	6178	27.08	6541	27.34	6340	31.48	6353	2.9	28.63	8.6
	5	5128	28.26	5352	28.56	5159	32.57	5213	2.3	29.80	8.1
	1	3170	31.82	3268	32.51	3099	36.12	3179	2.7	33.48	6.9
	0.5	2541	32.25	2605	33.03	2447	36.45	2531	3.1	33.91	6.6
	0.1	1497	33.09	1517	33.89	1351	36.98	1455	6.2	34.65	5.9
37.8	10	1486	37.01	1389	38.38	1278	40.08	1384	7.5	38.49	4.0
	5	1116	35.38	1030	36.80	921	38.29	1022	9.6	36.82	4.0
	1	583	32.28	522	33.65	458	33.99	521	11.9	33.31	2.7
	0.5	475	29.87	427	31.44	366	31.33	423	13.0	30.88	2.8
	0.1	315	23.94	288	25.57	241	24.57	281	13.4	24.69	3.3
50	10	532	31.47	525	33.92	513	34.17	523	1.8	33.19	4.5
	5	359	29.75	351	30.78	359	30.68	356	1.4	30.40	1.9
	1	227	23.91	216	23.66	231	24.14	225	3.5	23.90	1.0
	0.5	188	21.40	184	20.40	191	19.81	188	1.8	20.54	3.9
	0.1	155	15.07	155	14.24	155	13.01	155	0.2	14.11	7.4

d) Warm mix asphalt + 50% RAP with Evotherm

Test Temperature	Frequency	Sample 3		Sample 4		Sample 5		Average Modulus MPa	Modulus CoV (%)	Average Phase Angle Degree	Phase Angle CoV (%)
Degree Celsius	Hz	Modulus MPa	Phase Angle Degree	Modulus MPa	Phase Angle Degree	Modulus MPa	Phase Angle Degree				
4.4	10	20731	17.54	20701	24.09	18874	15.47	20102	5.3	19.03	23.6
	5	18482	16.06	17632	20.36	17330	14.29	17815	3.4	16.90	18.5
	1	14292	16.95	13079	18.52	13247	15.41	13539	4.9	16.96	9.2
	0.5	12843	18.34	11689	19.84	11696	16.72	12076	5.5	18.30	8.5
	0.1	9748	22.10	8850	23.41	8751	20.04	9116	6.0	21.85	7.8
21.1	10	9686	31.64	7632	26.88	7109	25.41	8142	16.7	27.98	11.6
	5	8054	31.52	6380	26.68	5921	25.88	6785	16.5	28.03	10.9
	1	5488	33.73	4259	30.28	3849	29.45	4532	18.8	31.15	7.3
	0.5	4606	33.82	3536	31.43	3161	30.42	3768	19.9	31.89	5.5
	0.1	3002	35.95	2151	34.23	1930	32.82	2361	24.0	34.33	4.6
37.8	10	2605	34.89	1942	35.01	2052	35.50	2200	16.2	35.13	0.9
	5	2155	34.53	1523	34.13	1640	35.03	1773	19.0	34.56	1.3
	1	1331	32.94	833	33.38	933	33.94	1032	25.5	33.42	1.5
	0.5	1148	32.19	670	31.78	763	32.15	860	29.5	32.04	0.7
	0.1	854	30.61	428	27.88	503	28.58	595	38.2	29.02	4.9
50	10	837	34.07	731	35.93	908	33.73	825	10.8	34.58	3.4
	5	624	31.48	533	33.34	709	31.44	622	14.1	32.09	3.4
	1	374	26.63	304	28.46	441	26.83	373	18.3	27.31	3.7
	0.5	319	24.74	244	25.22	379	24.61	314	21.5	24.86	1.3
	0.1	251	19.66	184	19.59	302	20.56	245	24.2	19.94	2.7

e) Warm mix asphalt + 70% RAP with Evotherm

Test Temperature	Frequency	Sample 2		Sample 3		Sample 4		Average Modulus MPa	Modulus CoV (%)	Average Phase Angle Degree	Phase Angle CoV (%)
Degree Celsius	Hz	Modulus MPa	Phase Angle Degree	Modulus MPa	Phase Angle Degree	Modulus MPa	Phase Angle Degree				
4.4	10	25729	20.13	23073	23.52	17696	18	22166	18.5	20.53	13.7
	5	23223	16.18	21463	24.19	15864	17	20183	19.0	19.14	23.0
	1	18072	17.01	16110	23.08	12407	17	15530	18.5	18.94	18.9
	0.5	15732	21.42	13678	24.94	11331	18	13580	16.2	21.39	16.7
	0.1	11274	23.58	9308	25.91	8942	21	9841	12.7	23.34	11.6
21.1	10	10503	24.23	9356	24.29	8885	28	9581	8.7	25.47	8.2
	5	8871	24.58	7932	23.43	7317	27	8040	9.7	25.04	7.5
	1	6070	28.13	5637	25.92	5098	30	5602	8.7	27.98	7.1
	0.5	5128	29.36	4863	26.91	4227	31	4739	9.8	28.97	6.5
	0.1	3365	32.32	3341	29.83	2747	34	3151	11.1	31.92	6.0
37.8	10	3197	32.78	3257	32.21	2210	35	2888	20.4	33.36	4.6
	5	2595	33.01	2750	33.19	1796	35	2380	21.5	33.85	3.8
	1	1488	34.32	1726	34.15	978	36	1397	27.3	34.86	3.1
	0.5	1203	33.76	1423	32.49	785	35	1137	28.5	33.80	3.9
	0.1	719	32.63	946	30.48	477	32	714	32.9	31.85	3.7
50	10	1209	35.27	1224	37.28	934	39	1122	14.5	37.13	4.8
	5	930	33.70	954	35.33	700	37	862	16.3	35.41	4.9
	1	486	30.84	499	31.81	360	34	448	17.1	32.15	4.7
	0.5	382	28.10	388	28.87	278	31	349	17.8	29.44	5.8
	0.1	253	22.17	253	22.21	191	25	232	15.5	23.10	6.8

f) Warm mix asphalt with Sylvaroad

Test Temperature	Frequency	Sample 1		Sample 2		Sample 3		Average Modulus MPa	Modulus CoV (%)	Average Phase Angle Degree	Phase Angle CoV (%)
Degree Celsius	Hz	Modulus MPa	Phase Angle Degree	Modulus MPa	Phase Angle Degree	Modulus MPa	Phase Angle Degree				
4.4	10	12685	23.23	11159	27.31	10807	21.19	11550	8.6	24	13.0
	5	10744	23.43	9572	27.25	9383	21.74	9900	7.4	24	11.7
	1	7376	26.98	6595	29.91	6593	25.73	6855	6.6	28	7.8
	0.5	6127	28.72	5497	31.98	5554	27.57	5726	6.1	29	7.8
	0.1	3922	33.84	3420	36.63	3533	32.33	3625	7.3	34	6.4
21.1	10	3249	35.41	3146	35.33	2974	35.35	3123	4.4	35	0.1
	5	2495	36.43	2452	36.96	2299	36.80	2415	4.3	37	0.7
	1	1220	39.05	1219	40.09	1111	39.74	1183	5.3	40	1.3
	0.5	881	38.97	897	39.96	812	39.79	864	5.2	40	1.3
	0.1	413	38.04	428	39.17	381	38.88	407	5.9	39	1.5
37.8	10	526	43.27	528	41.81	535	42.52	530	0.9	43	1.7
	5	334	41.93	327	44.25	337	43.25	333	1.6	43	2.7
	1	148	38.22	170	39.21	158	38.85	159	7.0	39	1.3
	0.5	116	35.66	139	36.58	125	36.50	127	9.3	36	1.4
	0.1	70	27.28	95	26.59	79	28.14	81	15.1	27	2.8
50	10	196	37.15	224	42.20	196	35.05	205	7.8	38	9.6
	5	130	35.62	144	40.53	122	35.99	132	8.7	37	7.3
	1	78	28.72	91	34.05	74	27.83	81	11.0	30	11.1
	0.5	61	22.51	68	25.96	56	19.94	61	9.8	23	13.2
	0.1	47	13.68	55	20.78	48	12.63	50	8.6	16	28.2

g) Warm mix asphalt + 25% RAP with Sylvaroad

Test Temperature	Frequency	Sample 1		Sample 2		Sample 3		Average Modulus MPa	Modulus CoV (%)	Average Phase Angle Degree	Phase Angle CoV (%)
Degree Celsius	Hz	Modulus MPa	Phase Angle Degree	Modulus MPa	Phase Angle Degree	Modulus MPa	Phase Angle Degree				
4.4	10	12289	16.33	12140	17.08	12110	21.95	12180	0.8	18	16.5
	5	10538	17.01	10949	16.62	10562	20.75	10683	2.2	18	12.6
	1	7687	20.32	8187	19.61	7730	22.72	7868	3.5	21	7.8
	0.5	7082	22.43	7144	21.68	6769	24.48	6998	2.9	23	6.3
	0.1	4971	27.03	5026	26.25	4495	28.64	4831	6.0	27	4.5
21.1	10	4622	33.87	4742	32.42	4262	33.33	4542	5.5	33	2.2
	5	3708	35.09	3780	33.30	3509	34.12	3666	3.8	34	2.6
	1	2125	37.88	2195	36.84	2024	37.22	2115	4.1	37	1.4
	0.5	1580	38.20	1727	37.23	1596	37.00	1634	4.9	37	1.7
	0.1	830	38.12	957	37.69	870	37.10	886	7.3	38	1.4
37.8	10	N/A	N/A	914	41.76	801	39.51	858	9.4	41	3.9
	5	N/A	N/A	659	42.94	546	40.60	602	13.2	42	4.0
	1	N/A	N/A	367	39.21	285	36.68	326	17.8	38	4.7
	0.5	N/A	N/A	304	36.90	230	33.20	267	19.7	35	7.5
	0.1	N/A	N/A	214	30.42	156	28.11	185	22.1	29	5.6
50	10	289	34.87	329	38.12	308	35.48	309	6.5	36	4.8
	5	168	39.40	213	41.59	189	37.57	190	12.0	40	5.1
	1	92	33.44	126	35.91	120	30.72	112	16.1	33	7.8
	0.5	70	27.87	83	27.47	92	24.40	82	13.9	27	7.1
	0.1	51	19.24	68	18.58	75	16.36	65	19.7	18	8.4

h) Warm mix asphalt + 50% RAP with Sylvaroad

Test Temperature	Frequency	Sample 1		Sample 2		Sample 3		Average Modulus MPa	Modulus CoV (%)	Average Phase Angle Degree	Phase Angle CoV (%)
Degree Celsius	Hz	Modulus MPa	Phase Angle Degree	Modulus MPa	Phase Angle Degree	Modulus MPa	Phase Angle Degree				
4.4	10	14737	19.46	15213	18.96	14752	16.34	14901	1.8	18	9.2
	5	12760	17.90	13682	18.93	13382	15.40	13275	3.5	17	10.4
	1	9331	19.90	10276	18.98	10275	17.76	9961	5.5	19	5.7
	0.5	8075	21.32	9165	20.34	9072	19.11	8771	6.9	20	5.5
	0.1	5811	25.18	6814	23.89	6566	23.63	6397	8.2	24	3.4
21.1	10	5169	28.76	6469	25.25	6127	25.22	5922	11.4	26	7.7
	5	4261	29.77	5383	26.55	5082	26.89	4909	11.8	28	6.4
	1	2601	33.14	3484	30.68	3263	30.93	3116	14.7	32	4.3
	0.5	2031	34.37	2881	31.45	2622	31.94	2511	17.3	33	4.8
	0.1	1126	36.24	1710	33.76	1507	34.54	1448	20.5	35	3.6
37.8	10	1282	41.30	1667	36.54	1305	38.47	1418	15.2	39	6.2
	5	927	41.71	1265	36.94	940	39.61	1044	18.3	39	6.1
	1	437	39.69	632	36.23	429	39.12	499	23.1	38	4.8
	0.5	337	38.03	504	34.97	325	38.16	389	25.8	37	4.9
	0.1	190	34.09	301	31.71	169	35.04	220	32.3	34	5.1
50	10	0	0.00	601	38.42	495	35.34	548	13.7	37	5.9
	5	0	0.00	386	40.95	289	38.18	338	20.3	40	5.0
	1	0	0.00	210	38.65	153	33.75	182	22.5	36	9.6
	0.5	0	0.00	160	35.70	124	31.20	142	18.1	33	9.5
	0.1	0	0.00	114	29.93	86	23.04	100	20.1	26	18.4

i) Warm mix asphalt + 70% RAP with Sylvaroad

Test Temperature	Frequency	Sample 1		Sample 2		Sample 3		Average Modulus MPa	Modulus CoV (%)	Average Phase Angle Degree	Phase Angle CoV (%)
Degree Celsius	Hz	Modulus MPa	Phase Angle Degree	Modulus MPa	Phase Angle Degree	Modulus MPa	Phase Angle Degree				
4.4	10	13847	15.82	16861	17.37	14319	22.36	15009	10.8	19	18.5
	5	12717	14.79	14902	16.61	12526	18.92	13382	9.9	17	12.3
	1	10085	16.42	11785	17.00	10028	18.73	10633	9.4	17	6.9
	0.5	8919	17.75	10633	18.31	9018	19.88	9523	10.1	19	5.9
	0.1	6808	20.59	7954	21.77	6965	23.35	7242	8.6	22	6.3
21.1	10	6102	24.73	6867	24.92	5439	25.91	6136	11.6	25	2.5
	5	5015	25.96	5703	25.94	4747	27.66	5155	9.6	27	3.7
	1	3343	30.24	3761	30.00	3173	32.20	3426	8.8	31	3.9
	0.5	2697	30.37	3126	31.01	2651	33.34	2825	9.3	32	5.0
	0.1	1590	34.09	1855	33.89	1475	37.33	1640	11.9	35	5.5
37.8	10	1589	37.52	1930	36.26	1761	37.21	1760	9.7	37	1.8
	5	1214	37.95	1478	36.66	1342	37.72	1345	9.8	37	1.8
	1	601	38.03	740	36.61	662	37.69	668	10.4	37	2.0
	0.5	473	37.20	577	35.43	526	36.84	525	9.8	36	2.6
	0.1	262	34.85	316	32.39	303	34.14	294	9.5	34	3.7
50	10	640	37.50	633	37.51	634	38.20	636	0.6	38	1.1
	5	404	41.85	387	40.49	426	39.22	406	4.8	41	3.2
	1	201	39.70	185	38.17	230	35.02	205	11.0	38	6.3
	0.5	162	38.21	134	35.39	178	31.47	158	14.1	35	9.7
	0.1	103	33.99	76	27.68	122	22.37	100	23.1	28	20.8

APPENDIX 4: WHEEL TRACKING

A4.1 HMA, WMA and WMA-RAP mixtures with Evotherm

Type of mix	ID	m1_mass in air (g)	m2_mass in water (g)	m3_mass of saturated sample (g)	Water temp. (°C)	Density of water (g/cm^3)	Bulk density G_{mb} (g/cm^3)	Maximum density G_{mm} (g/cm^3)	Air void (%)	Average air void (%)	Num. of cycle	Ave. Num. of cycle	CoV (%)
HMA	1	10380.5	5983.4	10421.0	19.4	0.998	2.335	2.452	4.78	4.96	3414	2922	24
	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A		N/A		
	3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A		N/A		
	4	10369.5	5996.6	10411.5	18.0	0.999	2.346	2.452	4.30		2430		
WMA-E	1	10448.5	6034.0	10531.0	18.6	0.999	2.321	2.459	5.59	5.33	1095	1401	28
	2	10281.5	5936.4	10341.0	19.0	0.998	2.330	2.459	5.24		1262		
	2	10155.0	5866.6	10218.0	17.6	0.999	2.331	2.459	5.17		1847		
25R-E	1	10294.0	5955.8	10371.5	17.2	0.999	2.329	2.468	5.62	5.68	6193	6134	8
	2	10271.5	5948.7	10348.5	17.2	0.999	2.332	2.468	5.49		6588		
	3	10280.0	5930.4	10355.5	17.2	0.999	2.321	2.468	5.95		5621		
50R-E	1	10160.5	5871.8	10259.0	17.8	0.999	2.314	2.463	6.05	5.37	17510	18576	9
	2	10183.0	5894.6	10289.0	17.8	0.999	2.315	2.463	5.99		20497		
	3	10283.0	5965.8	10315.0	16.8	0.999	2.362	2.463	4.08		17721		
70R-E	1	10426.0	6070.5	10523.0	15.7	0.999	2.339	2.470	5.29	5.50	75175	62543	20
	2	10335.0	5991.0	10424.5	15.0	0.999	2.329	2.470	5.72		50410		
	3	10339.0	6014.0	10438.5	15.0	0.999	2.334	2.470	5.49		62043		

A4.2 WMA + 50%RAP and WMA + 70%RAP with Evotherm in extended cases

Type of mix	ID	m1_mass in air (g)	m2_mass in water (g)	m3_mass of saturated sample (g)	Water temp. (°C)	Density of water (g/cm^3)	Bulk density G_{mb} (g/cm^3)	Maximum density G_{mm} (g/cm^3)	Air void (%)	Ave. air void (%)	Num. of cycle	Ave. Num. of cycle	CoV (%)
50R-S	1	10435	6002.5	10493	17.8	0.999	2.321	2.463	5.73	5.92	14361	12791	17
	2	10405	5990.5	10486.5	17.8	0.999	2.312	2.463	6.11		11221		
70R-S	1	10545.0	6097.0	10613.5	17.7	0.999	2.332	2.470	5.57	6.14	50161	44706	17
	2	10414.5	6015.5	10533	17.6	0.999	2.303	2.470	6.76		39251		

A4.3 WMA and WMA-RAP mixtures with Sylvaroad

Type of mix	ID	m1_mass in air (g)	m2_mass in water (g)	m3_mass of saturated sample (g)	Water temp. (°C)	Density of water (g/cm^3)	Bulk density G_{mb} (g/cm^3)	Maximum density G_{mm} (g/cm^3)	Air void (%)	Ave. air void (%)	Num. of cycle	Ave. Num. of cycle	CoV (%)
WMA - S	1	10274.0	5918.0	10364.0	15.6	0.999	2.309	2.459	6.10	5.21	988	1126	17
	2	10456.0	6056.0	10496.5	17.0	0.999	2.352	2.459	4.32		1264		
25R-S	1	10347.0	6000.2	10402.4	17.0	0.999	2.348	2.468	4.84	4.89	6401	5681	18
	2	10361.5	5979.5	10392.5	17.0	0.999	2.346	2.468	4.94		4961		
50R-S	1	10433.5	6035.0	10496.5	17.0	0.999	2.336	2.463	5.13	5.91	15121	12712	27
	2	10250.0	5910.0	10366.0	16.4	0.999	2.298	2.463	6.68		10302		
70R-S	1	10373.0	6009.0	10452.0	16.4	0.999	2.332	2.470	5.57	5.85	19011	20393	10
	2	10402.0	6019.0	10501.0	17.0	0.999	2.319	2.470	6.13		21775		

APPENDIX 5: RESILIENT MODULUS AND INDIRECT TENSILE STRENGTH

A5.1 Volumetric properties

Mixture type	ID	m1_mass in air (g)	m2_mass in water (g)	m3_mass of saturated sample (g)	Water temp. (°C)	Density of water (g/cm^3)	Bulk density G_{mb} (g/cm^3)	Maximum density G_{mm} (g/cm^3)	Air void (%)
HMA	1	888.77	508.73	889.36	15.9	0.999	2.333	2.452	4.86
	2	885.63	508.33	886.12	15.9	0.999	2.342	2.452	4.48
	3	898.14	512.77	898.65	15.9	0.999	2.325	2.452	5.16
WMA - E	1	868.68	499.51	869.3	13.4	0.999	2.347	2.459	4.54
	2	870.37	497	871.12	13.4	0.999	2.324	2.459	5.47
	3	896.18	511.65	896.81	15.9	0.999	2.324	2.459	5.45
25R - E	1	899.53	517.61	900.23	15.9	0.999	2.349	2.468	4.82
	2	905.24	521.84	905.91	15.9	0.999	2.355	2.468	4.58
	3	882.12	505.42	882.87	15.9	0.999	2.335	2.468	5.38
50R - E	1	886	512.4	888.12	13.4	0.999	2.356	2.463	4.33
	2	870	501.82	872.85	13.4	0.999	2.342	2.463	4.87
	3	869.97	496.59	870.81	16	0.999	2.322	2.463	5.69
	4	889.75	506.2	890.97	16	0.999	2.310	2.463	6.19
	5	872.05	499.13	872.71	16	0.999	2.332	2.463	5.30
WMA - S	1	866.01	491.86	866.8	17.6	0.999	2.307	2.459	6.15
	2	879.65	499.63	880.31	17.6	0.999	2.308	2.459	6.10
	3	886.7	506.17	887.27	17.6	0.999	2.324	2.459	5.46
	4	892.4	512.24	893.36	16	0.999	2.339	2.459	4.85
	5	884.59	506.46	885.7	16	0.999	2.330	2.459	5.22
25R - S	1	894.19	512.19	894.98	16	0.999	2.334	2.468	5.43
	2	884.58	506.1	885.28	16	0.999	2.331	2.468	5.55
	3	883.74	504.56	884.66	16	0.999	2.323	2.468	5.87
50R - S	1	895.54	512.56	896.46	16	0.999	2.330	2.463	5.36
	2	881.7	505.97	883.72	16	0.999	2.332	2.463	5.31
	3	882.42	500.88	883.73	16	0.999	2.303	2.463	6.50
	4	893.92	511.28	894.99	16	0.999	2.327	2.463	5.49

A5.2 Test results

Mix type	ID	H (mm)	D (mm)	Resilient modulus test			Indirect tensile strength test			
				M_r (MPa)	Average (MPa)	CoV (%)	Peak load (kN)	ITS (kPa)	Average (MPa)	CoV (%)
HMA	1	49.61	99	2494	2508	0.94	6854.46	889	881	1.04
	2	49.32	98.99	2494			6783.76	885		
	3	50.34	99.12	2535			6826.75	871		
WMA - E	1	48.04	99.16	2074	1997	3.96	5531.05	739	737	2.89
	2	48.75	99.2	2002			5754.72	758		
	3	50.26	99.02	1916			5590.78	715		
25R - E	1	49.92	99.04	2979	2878	7.05	8524.09	1098	1060	3.91
	2	50.49	98.95	3010			7970.28	1016		
	3	48.93	99.12	2644			8124.68	1067		
50R - E	1	49.09	99.05	4580	3946	15.68	11570.26	1515	1364	10.81
	2	48.55	99.04	3913			10235.27	1355		
	5	48.82	98.55	3344			9223.78	1221		
WMA - S	3	49.89	98.88	1548	1504	10.91	5055.53	652	602	7.31
	4	49.51	99.03	1322			4470.62	581		
	5	49.27	98.92	1641			4383.79	573		
25R - S	1	49.86	98.88	2034	2086	6.64	6592.37	851	849	1.93
	2	49.73	99	2243			6429.23	831		
	3	49.45	98.89	1981			6635.89	864		
50R - S	1	50.28	98.81	2707	2955	17.58	7716.29	989	1076	14.70
	2	49.29	98.75	2606			7492.78	980		
	3	50.18	98.85	3552			9803.64	1258		

APPENDIX 6: SEMI-CIRCULAR BENDING TEST

A6.1 Mixture designation and abbreviations

Abbreviation example	Designation
H5_n	Hot mix asphalt sample with 5% air void, sample number n
H7_n	Hot mix asphalt sample with 7% air void, sample number n
WE5_n	Warm mix asphalt, using Evotherm, with 5% air void, sample number n
WE7_n	Warm mix asphalt, using Evotherm, with 7% air void, sample number n
25E5_n	Warm mix asphalt adding 25% RAP, using Evotherm, with 5% air void, sample number n
25E7_n	Warm mix asphalt adding 25% RAP, using Evotherm, with 7% air void, sample number n
50E5_n	Warm mix asphalt adding 50% RAP, using Evotherm, with 5% air void, sample number n
50E7_n	Warm mix asphalt adding 50% RAP, using Evotherm, with 7% air void, sample number n
WS5_n	Warm mix asphalt, using Sylvaroad, with 5% air void, sample number n
WS7_n	Warm mix asphalt, using Sylvaroad, with 7% air void, sample number n
25S5_n	Warm mix asphalt adding 25% RAP, using Sylvaroad, with 5% air void, sample number n
25S7_n	Warm mix asphalt adding 25% RAP, using Sylvaroad, with 7% air void, sample number n
50S5_n	Warm mix asphalt adding 50% RAP, using Sylvaroad, with 5% air void, sample number n
50S7_n	Warm mix asphalt adding 50% RAP, using Sylvaroad, with 7% air void, sample number n

A6.2 Volumetric properties

a) Hot mix asphalt

ID	m1_mass in air (g)	m2_mass in water (g)	m3_mass of saturated sample (g)	Water temp. (°C)	Density of water (g/cm^3)	Bulk density G_{mb} (g/cm^3)	Maximum density G_{mm} (g/cm^3)	Air void (%)
H5_1	257.49	147.36	257.65	15.6	0.999	2.332	2.452	4.872
H5_2	260.18	148.67	260.34	15.6	0.999	2.328	2.452	5.066
H5_3	250.61	142.4	250.79	15.6	0.999	2.310	2.452	5.791
H5_4	255.59	145.78	255.78	15.6	0.999	2.321	2.452	5.325
H5_5	261.89	149.96	262.04	15.6	0.999	2.334	2.452	4.792
H5_6	266.83	152.93	266.98	15.6	0.999	2.337	2.452	4.671
H5_7	263.09	150.46	263.3	15.6	0.999	2.329	2.452	5.000
H5_8	260.38	148.59	260.74	15.6	0.999	2.319	2.452	5.400
H5_9	273.17	155.62	273.35	15.6	0.999	2.318	2.452	5.457
H5_10	272.51	155.74	272.68	15.6	0.999	2.328	2.452	5.048
H5_13	261.67	149.38	261.92	17.6	0.999	2.323	2.452	5.260
H5_14	257.37	146.62	257.57	17.6	0.999	2.317	2.452	5.482
H5_15	253.91	146.24	254.05	17.6	0.999	2.353	2.452	4.037
H5_16	261.61	150.79	261.78	17.6	0.999	2.355	2.452	3.959
H7_1	265.59	149.66	265.89	17.6	0.999	2.283	2.452	6.894
H7_2	260.84	147.26	261.1	17.6	0.999	2.289	2.452	6.639
H7_3	248.22	139.59	248.47	17.6	0.999	2.277	2.452	7.109
H7_4	244.36	137.16	244.62	17.6	0.999	2.272	2.452	7.345
H7_5	253.35	142.5	253.58	17.6	0.999	2.279	2.452	7.067
H7_6	259.34	146.31	259.63	17.6	0.999	2.286	2.452	6.750
H7_7	253.86	143.13	254.18	17.6	0.999	2.284	2.452	6.855
H7_8	251.45	141.86	251.73	17.6	0.999	2.286	2.452	6.748
H7_9	254.89	143.58	255.21	17.6	0.999	2.281	2.452	6.963
H7_10	254.56	143.31	254.89	17.6	0.999	2.279	2.452	7.042
H7_11	262.47	147.01	262.81	17.6	0.999	2.264	2.452	7.646
H7_12	260.17	146.26	260.51	17.6	0.999	2.275	2.452	7.213
H7_13	257.75	146.07	258.02	17.6	0.999	2.300	2.452	6.188
H7_14	263.81	149.48	264.11	17.6	0.999	2.299	2.452	6.227
H7_15	249.94	141.9	250.25	17.6	0.999	2.304	2.452	6.008
H7_16	258.35	146.27	258.62	17.6	0.999	2.297	2.452	6.304

b) Warm mix asphalt with Evotherm

ID	m1_mass in air (g)	m2_mass in water (g)	m3_mass of saturated sample (g)	Water temp. (°C)	Density of water (g/cm^3)	Bulk density G_{mb} (g/cm^3)	Maximum density G_{mm} (g/cm^3)	Air void (%)
WE5_1	266.63	151.87	266.77	17.6	0.999	2.318	2.459	5.706
WE5_2	260.73	148.03	260.9	17.6	0.999	2.308	2.459	6.134
WE5_3	272.07	155.88	272.26	17.6	0.999	2.335	2.459	5.006
WE5_4	267.48	153.39	267.66	17.6	0.999	2.338	2.459	4.884
WE5_5	258.48	147.97	258.65	17.6	0.999	2.333	2.459	5.103
WE5_6	266.91	152.05	267.11	17.6	0.999	2.317	2.459	5.738
WE5_7	257.62	146.99	257.79	17.6	0.999	2.323	2.459	5.521
WE5_8	260.38	148.27	260.54	17.6	0.999	2.317	2.459	5.759
WE5_9	262.32	148.36	262.51	17.6	0.999	2.296	2.459	6.621
WE5_10	269.9	154.53	270.09	17.6	0.999	2.333	2.459	5.095
WE5_11	263.36	151.22	263.53	17.6	0.999	2.343	2.459	4.715
WE5_12	254.47	145.42	254.66	17.6	0.999	2.327	2.459	5.344
WE5_13	263.77	151.2	263.98	17.6	0.999	2.336	2.459	4.964
WE5_14	261.2	149.83	261.39	17.6	0.999	2.339	2.459	4.861
WE7_1	259.46	145.77	259.72	16.7	0.999	2.275	2.459	7.477
WE7_2	257.71	144.66	257.94	16.7	0.999	2.273	2.459	7.557
WE7_3	253.87	143.15	254.16	16.7	0.999	2.285	2.459	7.073
WE7_4	248.35	139.03	248.6	16.7	0.999	2.264	2.459	7.898
WE7_5	249.24	140.49	249.45	16.7	0.999	2.285	2.459	7.051
WE7_6	254.27	142.25	254.55	16.7	0.999	2.262	2.459	7.995
WE7_7	252.31	140.54	252.53	16.7	0.999	2.251	2.459	8.452
WE7_8	253.82	142.21	254.08	16.7	0.999	2.267	2.459	7.805
WE7_9	266.56	150.16	266.76	16.7	0.999	2.284	2.459	7.105
WE7_10	251.15	141.13	251.31	16.7	0.999	2.277	2.459	7.376
WE7_11	263.94	149.43	264.11	16.7	0.999	2.299	2.459	6.478
WE7_12	246.23	138.17	246.45	16.7	0.999	2.272	2.459	7.597
WE7_13	250.68	140.5	250.91	16.7	0.999	2.268	2.459	7.742
WE7_14	259.29	145.8	259.46	16.7	0.999	2.279	2.459	7.302

Supplement samples								
WE-S1	261.07	148.05	261.45	19.7	0.998	2.298	2.459	6.545
WE-S2	252.6	143.72	252.87	19.7	0.998	2.310	2.459	6.056

c) Warm mix asphalt + 25% RAP with Evotherm

ID	m1_mass in air (g)	m2_mass in water (g)	m3_mass of saturated sample (g)	Water temp. (°C)	Density of water (g/cm^3)	Bulk density G_{mb} (g/cm^3)	Maximum density G_{mm} (g/cm^3)	Air void (%)
25E5_1	259.56	149.18	259.75	15.6	0.999	2.345	2.468	4.961
25E5_2	265.26	152.75	265.47	15.6	0.999	2.351	2.468	4.727
25E5_3	262.02	149.37	262.25	17.6	0.999	2.319	2.468	6.024
25E5_4	261.76	150	261.93	17.6	0.999	2.336	2.468	5.320
25E5_5	257.46	147.36	257.66	17.6	0.999	2.332	2.468	5.500
25E5_6	260.31	149.05	260.47	17.6	0.999	2.334	2.468	5.414
25E5_7	265.83	151.95	266.01	17.6	0.999	2.328	2.468	5.644
25E5_8	264.54	151.03	264.74	17.6	0.999	2.324	2.468	5.813
25E5_9	260.27	149.14	260.4	17.6	0.999	2.337	2.468	5.292
25E5_10	259.65	149.27	259.82	17.6	0.999	2.346	2.468	4.911
25E5_11	260.36	148.95	260.56	17.6	0.999	2.330	2.468	5.557
25E5_12	259.66	148.82	259.87	17.6	0.999	2.336	2.468	5.336
25E5_13	258.29	147.07	258.49	17.6	0.999	2.316	2.468	6.148
25E5_14	257.35	147.32	257.55	17.6	0.999	2.332	2.468	5.480
25E7_1	258.63	145.99	258.91	17.6	0.999	2.288	2.468	7.273
25E7_2	257.23	145.14	257.49	17.6	0.999	2.287	2.468	7.307
25E7_3	247.88	138.8	248.2	17.6	0.999	2.264	2.468	8.267
25E7_4	254.28	143.09	254.57	17.6	0.999	2.279	2.468	7.655
25E7_5	256.51	144.6	256.81	17.6	0.999	2.284	2.468	7.451
25E7_6	264.84	149.9	265.15	17.6	0.999	2.296	2.468	6.966
25E7_7	258.23	146.24	258.52	17.6	0.999	2.298	2.468	6.888
25E7_8	254.22	141.7	254.51	17.6	0.999	2.251	2.468	8.765
25E7_9	266.81	149.38	267.15	17.6	0.999	2.263	2.468	8.279
25E7_10	256.97	143.45	257.23	17.6	0.999	2.256	2.468	8.564
25E7_11	252.38	141.68	252.69	17.6	0.999	2.271	2.468	7.957
25E7_12	261.8	147.18	262.05	17.6	0.999	2.277	2.468	7.730
25E7_13	258.44	144.65	258.68	17.6	0.999	2.264	2.468	8.243
25E7_14	252.9	140.81	253.19	17.6	0.999	2.248	2.468	8.891
25E7_15	257.21	144.18	257.54	17.6	0.999	2.267	2.468	8.140
25E7_16	258.25	144.86	258.6	17.6	0.999	2.268	2.468	8.077

Supplement samples								
25E-S1	258.22	148.5	258.43	19.6	0.998	2.344	2.468	4.997
25E-S2	259.31	149.3	259.56	19.6	0.998	2.347	2.468	4.881

d) Warm mix asphalt + 50% RAP with Evotherm

ID	m1_mass in air (g)	m2_mass in water (g)	m3_mass of saturated sample (g)	Water temp. (°C)	Density of water (g/cm^3)	Bulk density G_{mb} (g/cm^3)	Maximum density G_{mm} (g/cm^3)	Air void (%)
50E5_1	259.88	147.81	260.22	16.6	0.999	2.310	2.463	6.211
50E5_2	263.14	150.35	263.5	16.6	0.999	2.323	2.463	5.655
50E5_3	258.58	147.55	258.9	16.6	0.999	2.320	2.463	5.791
50E5_4	263.82	150.2	264.12	16.6	0.999	2.314	2.463	6.051
50E5_5	262.57	149.49	262.8	16.6	0.999	2.315	2.463	5.992
50E5_6	255.54	145.89	255.84	16.6	0.999	2.322	2.463	5.713
50E5_7	261.7	149.37	261.93	16.6	0.999	2.323	2.463	5.680
50E5_8	261.12	148.1	261.54	16.6	0.999	2.300	2.463	6.619
50E5_9	269.01	152.75	269.38	16.6	0.999	2.304	2.463	6.428
50E5_10	255.97	145.68	256.26	16.6	0.999	2.312	2.463	6.093
50E5_11	248.83	141.77	249.12	16.6	0.999	2.316	2.463	5.966
50E5_12	263.15	149.64	263.47	16.6	0.999	2.309	2.463	6.215
50E7_1	248.77	140.05	249.12	16.6	0.999	2.279	2.463	7.471
50E7_2	256.49	144.75	256.87	16.6	0.999	2.285	2.463	7.195
50E7_3	243.84	137.16	244.19	16.6	0.999	2.276	2.463	7.576
50E7_4	246.47	138.85	246.82	16.6	0.999	2.280	2.463	7.392
50E7_5	257.7	145.58	258.03	16.6	0.999	2.289	2.463	7.030
50E7_6	252.38	141.95	252.7	16.6	0.999	2.277	2.463	7.552
50E7_7	247.75	139.1	248.23	16.6	0.999	2.268	2.463	7.901
50E7_8	256.43	144.75	256.81	16.6	0.999	2.286	2.463	7.167
50E7_9	248.57	140.56	248.92	16.6	0.999	2.292	2.463	6.939
50E7_10	250.54	141.32	250.84	16.6	0.999	2.285	2.463	7.195
50E7_11	252.19	142.35	252.51	16.6	0.999	2.287	2.463	7.127
50E7_12	257.23	145.27	257.57	16.6	0.999	2.288	2.463	7.076

Supplement samples								
50E-S1	250.73	142.05	251.16	19.7	0.998	2.293	2.463	6.869
50E-S2	251.08	142.52	251.41	19.7	0.998	2.301	2.463	6.551
50E-S3	250.71	143.16	251.03	19.7	0.998	2.320	2.463	5.806
50E-S4	250.48	142.52	250.81	19.7	0.998	2.308	2.463	6.258

e) Warm mix asphalt with Sylvaroad

ID	m1_mass in air (g)	m2_mass in water (g)	m3_mass of saturated sample (g)	Water temp. (°C)	Density of water (g/cm^3)	Bulk density G_{mb} (g/cm^3)	Maximum density G_{mm} (g/cm^3)	Air void (%)
WS5_1	261.19	148.71	261.44	17.6	0.999	2.315	2.459	5.852
WS5_2	262.64	149.07	262.83	17.6	0.999	2.306	2.459	6.186
WS5_3	258.59	147.74	258.82	17.6	0.999	2.326	2.459	5.405
WS5_4	259.68	147.37	259.91	17.6	0.999	2.305	2.459	6.238
WS5_5	258.3	146.87	258.54	17.6	0.999	2.311	2.459	6.010
WS5_6	263.3	149.99	263.56	17.6	0.999	2.316	2.459	5.793
WS5_7	262.8	149.8	263.01	17.6	0.999	2.319	2.459	5.673
WS5_8	261.52	149.66	261.77	17.6	0.999	2.330	2.459	5.212
WS5_9	260.67	148.82	260.91	17.6	0.999	2.323	2.459	5.503
WS5_10	254.74	145.33	255	17.6	0.999	2.320	2.459	5.615
WS5_11	252.2	143.7	252.42	17.6	0.999	2.317	2.459	5.739
WS5_12	263.41	150.54	263.67	17.6	0.999	2.326	2.459	5.387
WS5_13	257.23	146.07	257.49	17.6	0.999	2.306	2.459	6.189
WS5_14	257.81	147.4	258.05	17.6	0.999	2.328	2.459	5.323
WS5_15	258.96	147.13	259.21	17.6	0.999	2.308	2.459	6.114
WS5_16	262.96	149.67	263.24	17.6	0.999	2.313	2.459	5.915
WS5_17	247.75	141.58	248.01	17.6	0.999	2.325	2.459	5.410
WS5_18	250.43	143.4	250.7	17.6	0.999	2.332	2.459	5.162
WS7_1	251.79	141.38	252.1	16.7	0.999	2.272	2.459	7.593
WS7_2	250.75	140.73	251.02	16.7	0.999	2.271	2.459	7.615
WS7_3	255.66	143.39	255.92	16.7	0.999	2.270	2.459	7.681
WS7_4	254.62	143.18	254.89	16.7	0.999	2.277	2.459	7.382
WS7_5	254.84	143.26	255.11	16.7	0.999	2.276	2.459	7.418
WS7_6	261.25	147.22	261.55	16.7	0.999	2.283	2.459	7.148
WS7_7	251.7	141.25	251.99	16.7	0.999	2.271	2.459	7.642
WS7_8	257.1	144.42	257.46	16.7	0.999	2.272	2.459	7.580
WS7_9	255.46	143.78	255.72	16.7	0.999	2.280	2.459	7.267
WS7_10	258.27	145.37	258.54	16.7	0.999	2.280	2.459	7.266
WS7_11	251.19	141.22	251.51	16.7	0.999	2.275	2.459	7.453
WS7_12	261.83	147.31	262.13	16.7	0.999	2.278	2.459	7.339

Supplement samples								
WS-S1	270.2	153.05	270.45	19.7	0.998	2.297	2.459	6.572
WS-S2	260.85	148.1	261.11	19.7	0.998	2.304	2.459	6.301
WS-S3	264.22	150.94	264.49	19.7	0.998	2.322	2.459	5.542
WS-S4	263.98	150.66	264.3	19.7	0.998	2.318	2.459	5.703

f) Warm mix asphalt + 25% RAP with Sylvaroad

ID	m1_mass in air (g)	m2_mass in water (g)	m3_mass of saturated sample (g)	Water temp. (°C)	Density of water (g/cm^3)	Bulk density G_{mb} (g/cm^3)	Maximum density G_{mm} (g/cm^3)	Air void (%)
25S5_1	266.68	152.17	266.95	16.7	0.999	2.321	2.468	5.936
25S5_2	263.64	150.5	263.95	16.7	0.999	2.322	2.468	5.918
25S5_3	260.01	148.73	260.36	16.7	0.999	2.327	2.468	5.701
25S5_4	262.53	150.16	262.78	16.7	0.999	2.329	2.468	5.624
25S5_5	255.15	145.58	255.41	16.7	0.999	2.321	2.468	5.947
25S5_6	253.23	143.98	253.42	16.7	0.999	2.312	2.468	6.322
25S5_7	259.1	147.39	259.33	16.7	0.999	2.312	2.468	6.291
25S5_8	261.73	149.3	261.95	16.7	0.999	2.321	2.468	5.936
25S5_9	255.3	145.64	255.58	16.7	0.999	2.320	2.468	5.986
25S5_10	257.01	146.49	257.25	16.7	0.999	2.318	2.468	6.057
25S5_11	260.17	149.08	260.4	16.7	0.999	2.335	2.468	5.380
25S5_12	257.75	147.61	257.98	16.7	0.999	2.333	2.468	5.453
25S7_1	250.27	140.69	250.53	16.7	0.999	2.276	2.468	7.754
25S7_2	245.13	137.48	245.39	16.7	0.999	2.269	2.468	8.033
25S7_3	250.32	141.09	250.63	16.7	0.999	2.283	2.468	7.483
25S7_4	250.24	140.79	250.52	16.7	0.999	2.278	2.468	7.673
25S7_5	252.51	141.46	252.74	16.7	0.999	2.267	2.468	8.133
25S7_6	255.01	143.16	255.28	16.7	0.999	2.272	2.468	7.918
25S7_7	242.64	136.68	242.9	16.7	0.999	2.282	2.468	7.518
25S7_8	251.97	142.05	252.22	16.7	0.999	2.285	2.468	7.406
25S7_9	247.67	139.44	247.95	16.7	0.999	2.280	2.468	7.593
25S7_10	253.44	142.42	253.72	16.7	0.999	2.275	2.468	7.811
25S7_11	254.54	143.42	254.81	16.7	0.999	2.283	2.468	7.486
25S7_12	245.7	137.93	245.98	16.7	0.999	2.272	2.468	7.938

Supplement samples								
25S-S1	272.57	156.17	272.88	19.7	0.998	2.331	2.468	5.543
25S-S2	263.88	151.19	264.16	19.7	0.998	2.331	2.468	5.527
25S-S3	256.1	145.69	256.44	19.7	0.998	2.308	2.468	6.474
25S-S4	257.28	146.32	257.52	19.7	0.998	2.309	2.468	6.424

g) Warm mix asphalt + 50% RAP with Sylvaroad

ID	m1_mass in air (g)	m2_mass in water (g)	m3_mass of saturated sample (g)	Water temp. (°C)	Density of water (g/cm^3)	Bulk density G_{mb} (g/cm^3)	Maximum density G_{mm} (g/cm^3)	Air void (%)
50S5_1	250.64	141.61	250.98	16.7	0.999	2.289	2.463	7.031
50S5_2	252.18	142.29	252.49	16.7	0.999	2.286	2.463	7.164
50S5_3	255.21	144.94	255.45	16.7	0.999	2.307	2.463	6.312
50S5_4	251.61	143.35	251.85	16.7	0.999	2.317	2.463	5.923
50S5_5	255.16	144.54	255.42	16.7	0.999	2.299	2.463	6.643
50S5_6	252.94	143.43	253.2	16.7	0.999	2.302	2.463	6.520
50S5_7	250.84	141.46	251.14	16.7	0.999	2.285	2.463	7.220
50S5_8	258.64	146.78	258.86	16.7	0.999	2.305	2.463	6.383
50S5_9	259.79	147.5	260.07	16.7	0.999	2.306	2.463	6.376
50S5_10	250.52	141.29	250.88	16.7	0.999	2.284	2.463	7.262
50S5_11	256.78	146.48	257.04	16.7	0.999	2.320	2.463	5.779
50S5_12	259.09	147.92	259.3	16.7	0.999	2.324	2.463	5.631
50S7_1	256.52	146.38	256.83	16.7	0.999	2.320	2.463	5.780
50S7_2	255.53	145.49	255.82	16.7	0.999	2.314	2.463	6.042
50S7_3	253.66	143.12	253.98	16.7	0.999	2.286	2.463	7.175
50S7_4	253.64	143.05	253.94	16.7	0.999	2.285	2.463	7.208
50S7_5	251.48	141.94	251.82	16.7	0.999	2.286	2.463	7.152
50S7_6	250.74	141.39	251.15	16.7	0.999	2.282	2.463	7.324
50S7_7	257.76	146.65	258.05	16.7	0.999	2.312	2.463	6.132
50S7_8	256.97	146.3	257.29	16.7	0.999	2.313	2.463	6.074
50S7_9	252.16	142.65	252.48	16.7	0.999	2.294	2.463	6.859
50S7_10	253.06	143.64	253.4	16.7	0.999	2.303	2.463	6.467
50S7_11	253.12	143.61	253.31	16.7	0.999	2.305	2.463	6.393
50S7_12	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Supplement samples								
50S-S1	263.48	149.15	263.86	19.7	0.998	2.292	2.463	6.911
50S-S2	267.48	151.53	267.8	19.7	0.998	2.296	2.463	6.766
50S-S3	266.54	151.57	266.83	19.7	0.998	2.308	2.463	6.279
50S-S4	265.67	150.95	265.91	19.7	0.998	2.306	2.463	6.342
50S-S5	264.74	152.37	265.01	19.7	0.998	2.346	2.463	4.747
50S-S6	263.11	151.46	263.38	19.7	0.998	2.346	2.463	4.725
50S-S7	260.2	148.77	260.44	19.7	0.998	2.325	2.463	5.567
50S-S8	256.6	146.8	256.82	19.7	0.998	2.328	2.463	5.477

A6.3 Test results

a) Hot mix asphalt

HMA	Fracture energy (N.mm^{-1})	Maximum Tensile stress (kPa)	ε_{max} (%)	HMA	Fracture energy (N.mm^{-1})	Maximum Tensile stress (kPa)	ε_{max} (%)
Notch length - 5mm				Notch length - 5mm			
H5_1	0.2205	489.53	2.37	H7_1	0.1960	385.90	2.64
H5_2	0.1969	454.73	2.31	H7_2	0.1859	389.01	2.61
H5_3	0.1757	398.26	2.35	H7_3	0.1825	351.88	2.90
Average	0.1977	447.51	2.34	Average	0.1881	375.60	2.72
SD	0.02	46.06	0.03	SD	0.01	20.60	0.16
CV(%)	11.34	10.29	1.33	CV(%)	3.75	5.48	5.98
Notch length - 10mm				Notch length - 10mm			
H5_4	0.1622	328.94	2.39	H7_4	0.1194	249.48	2.33
H5_5	0.1613	357.01	2.00	H7_5	0.1281	268.10	2.14
H5_6	0.1735	350.58	2.25	H7_6	0.1282	254.39	2.23
Average	0.1657	345.51	2.21	Average	0.1253	257.32	2.23
SD	0.01	14.70	0.20	SD	0.01	9.65	0.09
CV(%)	4.11	4.26	8.94	CV(%)	4.02	3.75	4.13
Notch length - 15mm				Notch length - 15mm			
H5_7	0.1457	286.15	1.88	H7_7	0.1080	188.48	2.34
H5_8	0.1574	289.65	2.00	H7_8	0.1291	213.31	2.33
H5_9	0.1452	243.35	2.27	H7_9	0.1172	203.48	2.33
Average	0.1495	273.05	2.05	Average	0.1181	201.76	2.33
SD	0.01	25.78	0.20	SD	0.01	12.50	0.01
CV(%)	4.62	9.44	9.78	CV(%)	8.98	6.20	0.39
Notch length - 20mm				Notch length - 20mm			
H5_10	0.0970	167.54	1.84	H7_10	0.1121	154.98	2.23
H5_13	0.0949	173.49	1.71	H7_11	0.0961	135.14	2.22
H5_14	0.0943	154.28	1.84	H7_12	0.0770	112.70	2.24
Average	0.0954	165.10	1.79	Average	0.0951	134.27	2.23
SD	0.00	9.83	0.07	SD	0.02	21.15	0.01
CV(%)	1.50	5.95	3.98	CV(%)	18.46	15.75	0.49

b) Warm mix asphalt with Evotherm

WMA-E	Fracture energy ($N.mm^{-1}$)	Maximum Tensile stress (kPa)	ε_{max} (%)	WMA-E	Fracture energy ($N.mm^{-1}$)	Maximum Tensile stress (kPa)	ε_{max} (%)
Notch length - 5mm				Notch length - 5mm			
WE5_1	0.1870	358.19	2.68	WE7_1	0.1445	292.42	2.64
WE5_3	0.1707	391.37	2.40	WE7_2	0.1408	282.06	2.60
WE5_4	0.1684	364.26	2.64	WE7_3	0.1565	287.30	2.83
Average	0.1788	374.78	2.54	Average	0.1472	287.26	2.69
SD	0.01	23.47	0.20	SD	0.01	5.18	0.12
CV(%)	6.45	6.26	7.95	CV(%)	5.57	1.80	4.47
Notch length - 10mm				Notch length - 10mm			
WE5_5	0.1495	265.6630	2.4331	WE7_4	0.0754	183.9813	1.7923
WE5_6	0.1323	260.54	2.27	WE7_5	0.1002	197.5033	2.13
WE5_7	0.0915	250.63	1.67	WE7_8	0.0763	183.9651	1.69
Average	0.1244	258.95	2.12	Average	0.0840	188.4832	1.87
SD	0.03	7.64	0.40	SD	0.01	7.81	0.23
CV(%)	23.92	2.95	18.93	CV(%)	16.74	4.14	12.16
Notch length - 15mm				Notch length - 15mm			
WE5_8	0.0986	188.78	1.94	WE7_9	0.0882	163.60	2.04
WE5_10	0.0992	198.36	1.84	WE7_10	0.1054	210.95	1.83
WE5_11	0.0912	209.38	1.73	WE7_11	0.0893	205.05	1.73
Average	0.0952	203.87	1.78	Average	0.0943	193.20	1.87
SD	0.01	7.79	0.07	SD	0.01	25.80	0.16
CV(%)	5.91	3.82	4.18	CV(%)	10.20	13.36	8.43
Notch length - 20mm				Notch length - 20mm			
WE5_12	0.0744	138.77	1.69	WE7_12	0.0750	139.79	1.69
WE5_13	0.1007	166.20	2.02	WE7_13	0.1003	165.38	2.02
WE5_14	0.0905	154.65	1.81	WE7_14	0.0903	154.32	1.81
Average	0.0885	153.21	1.84	Average	0.0885	153.16	1.84
SD	0.01	13.77	0.17	SD	0.01	12.83	0.17
CV(%)	14.98	8.99	9.01	CV(%)	14.40	8.38	9.03

c) Warm mix asphalt + 25% RAP with Evotherm

25R-E	Fracture energy ($N.mm^{-1}$)	Maximum Tensile stress (kPa)	ε_{max} (%)	25R-E	Fracture energy ($N.mm^{-1}$)	Maximum Tensile stress (kPa)	ε_{max} (%)
Notch length - 5mm				Notch length - 5mm			
25E5_1	0.2576	529.61	2.33	25E7_1	0.1740	394.10	2.14
25E-S1	0.2497	610.49	2.02	25E7_2	0.1774	411.71	2.06
25E5_4	0.2540	583.22	2.35	25E7_3	0.1530	393.76	1.98
Average	0.2538	574.44	2.23	Average	0.1681	399.86	2.06
SD	0.00	41.15	0.18	SD	0.01	10.27	0.08
CV(%)	1.55	7.16	8.26	CV(%)	7.84	2.57	3.94
Notch length - 10mm				Notch length - 10mm			
25E5_5	0.1816	417.58	2.14	25E7_4	0.1151	307.39	1.69
25E5_6	0.1413	373.64	1.55	25E7_5	0.1132	310.99	1.57
25E-S2	0.1767	431.20	1.73	25E7_6	0.1038	269.57	1.78
Average	0.1665	407.47	1.81	Average	0.1107	295.98	1.68
SD	0.02	30.08	0.31	SD	0.01	22.94	0.10
CV(%)	13.18	7.38	16.91	CV(%)	5.51	7.75	6.24
Notch length - 15mm				Notch length - 15mm			
25E5_8	0.1291	292.64	1.63	25E7_7	0.1300	280.1827	1.7733
25E5_9	0.1295	307.31	1.59	25E7_9	0.0833	207.9648	1.5266
25E5_10	0.1569	352.50	1.65	25E7_11	0.1043	223.6321	1.6503
Average	0.1385	317.48	1.62	Average	0.1059	237.2599	1.6501
SD	0.02	31.20	0.03	SD	0.0234	37.9887	0.1234
CV(%)	11.53	9.83	1.95	CV(%)	22.0599	16.0114	7.4763
Notch length - 20mm				Notch length - 20mm			
25E5_11	0.1237	237.25	1.52	25E7_12	0.0686	155.01	1.32
25E5_12	0.0916	215.99	1.28	25E7_15	0.0616	142.13	1.28
25E5_14	0.1124	233.86	1.48	25E7_16	0.0901	182.78	1.73
Average	0.1092	229.04	1.43	Average	0.0734	159.97	1.44
SD	0.02	11.42	0.13	SD	0.01	20.78	0.25
CV(%)	14.88	4.99	9.22	CV(%)	20.24	12.99	17.34

d) Warm mix asphalt + 50% RAP with Evotherm

50R-E	Fracture energy ($N.mm^{-1}$)	Maximum Tensile stress (kPa)	ε_{max} (%)	50R-E	Fracture energy ($N.mm^{-1}$)	Maximum Tensile stress (kPa)	ε_{max} (%)
Notch length - 5mm				Notch length - 5mm			
50E5_1	0.2033	659.32	1.74	50E7_1	0.1586	514.49	1.72
50E5_2	0.2147	670.95	1.63	50E7_2	0.2475	663.72	2.05
50E5_3	0.1954	696.73	1.43	50E7_3	0.2260	648.42	1.82
Average	0.2045	675.67	1.60	Average	0.2107	608.88	1.86
SD	0.01	19.15	0.16	SD	0.05	82.10	0.17
CV(%)	4.73	2.83	9.90	CV(%)	22.02	13.48	9.05
Notch length - 10mm				Notch length - 10mm			
50E5_4	0.2262	606.63	1.74	50E7_4	0.2339	527.09	2.03
50E5_5	0.1965	593.43	1.45	50E7_5	0.1559	454.49	1.61
50E5_6	0.1981	626.47	1.43	50E7_6	0.1797	515.94	1.72
Average	0.2069	608.84	1.54	Average	0.1898	499.17	1.78
SD	0.02	16.63	0.17	SD	0.04	39.10	0.21
CV(%)	8.08	2.73	11.23	CV(%)	21.05	7.83	12.02
Notch length - 15mm				Notch length - 15mm			
50E5_7	0.1897	523.62	1.32	50E7_7	0.1197	342.36	1.32
50E-S3	0.1239	422.23	1.14	50E7_8	0.1080	346.56	1.16
50E5_9	0.1342	408.28	1.30	50E7_9	0.1311	369.21	1.36
Average	0.1568	472.93	1.23	Average	0.1196	352.71	1.28
SD	0.05	71.69	0.13	SD	0.01	14.44	0.11
CV(%)	29.68	15.16	10.73	CV(%)	9.66	4.09	8.51
Notch length - 20mm				Notch length - 20mm			
50E5_10	0.1225	315.27	1.18	50E7_10	0.0793	261.16	0.89
50E5_11	0.0855	291.23	0.89	50E7_11	0.0986	282.77	1.12
50E5_12	0.1098	304.04	1.26	50E7_12	0.0853	263.92	1.05
Average	0.1059	303.51	1.11	Average	0.0877	269.28	1.02
SD	0.02	12.03	0.19	SD	0.01	11.76	0.12
CV(%)	17.75	3.96	17.57	CV(%)	11.27	4.37	11.60

e) Warm mix asphalt with Sylvaroad

WMA-S	Fracture energy ($N.mm^{-1}$)	Maximum Tensile stress (kPa)	ε_{max} (%)	WMA-S	Fracture energy ($N.mm^{-1}$)	Maximum Tensile stress (kPa)	ε_{max} (%)
Notch length - 5mm				Notch length - 5mm			
WS5_1	0.0823	216.02	2.11	WS7_1	0.0896	196.71	2.33
WS5_3	0.1110	248.84	2.48	WS7_2	0.0720	192.89	2.02
WS5_6	0.1259	246.78	2.56	WS7_3	0.1002	196.97	2.72
Average	0.1064	237.21	2.38	Average	0.0873	195.52	2.36
SD	0.02	18.39	0.24	SD	0.01	2.28	0.35
CV(%)	20.80	7.75	10.24	CV(%)	16.34	1.17	14.87
Notch length - 10mm				Notch length - 10mm			
WS5_7	0.0943	179.37	2.29	WS7_4	0.0717	134.40	2.31
WS5_8	0.0575	164.61	1.59	WS7_5	0.0581	126.89	2.00
WS5_9	0.0974	187.70	2.48	WS7_6	0.0626	131.16	2.22
Average	0.0830	177.23	2.12	Average	0.0641	130.82	2.18
SD	0.02	11.69	0.47	SD	0.01	3.77	0.16
CV(%)	26.74	6.60	22.06	CV(%)	10.79	2.88	7.28
Notch length - 15mm				Notch length - 15mm			
WS5_10	0.0813	159.03	2.04	WS7_7	0.0579	100.46	2.17
WS5_11	0.0591	128.46	1.82	WS7_8	0.0494	90.01	2.10
WS5_12	0.0696	127.20	2.05	WS7_9	0.0678	109.84	2.31
Average	0.0702	143.74	1.93	Average	0.0584	100.10	2.19
SD	0.02	21.62	0.16	SD	0.01	9.92	0.10
CV(%)	22.45	15.04	8.28	CV(%)	15.79	9.91	4.76
Notch length - 20mm				Notch length - 20mm			
WS5_16	0.0535	96.26	1.71	WS7_10	0.0305	70.34	1.30
WS5_17	0.0705	108.06	1.97	WS7_11	0.0638	89.06	2.14
WS5_18	0.0572	93.92	1.72	WS7_12	0.0485	78.96	1.93
Average	0.0604	99.42	1.80	Average	0.0476	79.45	1.79
SD	0.01	7.58	0.15	SD	0.02	9.37	0.44
CV(%)	14.83	7.62	8.08	CV(%)	34.96	11.79	24.62

f) Warm mix asphalt + 25% RAP with Sylvaroad

25R-S	Fracture energy ($N.mm^{-1}$)	Maximum Tensile stress (kPa)	ε_{max} (%)	25R-S	Fracture energy ($N.mm^{-1}$)	Maximum Tensile stress (kPa)	ε_{max} (%)
Notch length - 5mm				Notch length - 5mm			
25S5_1	0.1840	407.34	2.27	25S7_1	0.1357	294.91	2.21
25S5_2	0.1403	365.98	1.80	25S7_2	0.1188	295.20	1.94
25S5_3	0.1461	381.47	2.03	25S7_3	0.1033	298.37	1.80
Average	0.1568	384.93	2.03	Average	0.1272	295.06	2.08
SD	0.02	20.90	0.24	SD	0.01	0.21	0.19
CV(%)	15.15	5.43	11.70	CV(%)	9.38	0.07	9.03
Notch length - 10mm				Notch length - 10mm			
25S5_4	0.1165	263.97	1.86	25S7_4	0.1263	280.35	1.92
25S5_5	0.1416	299.61	2.04	25S7_5	0.0797	195.92	1.90
25S-S2	0.1578	358.41	2.09	25S7_6	0.1280	253.88	2.13
Average	0.1386	307.33	2.00	Average	0.1113	243.38	1.98
SD	0.02	47.69	0.12	SD	0.03	43.19	0.13
CV(%)	15.02	15.52	6.01	CV(%)	24.62	17.74	6.32
Notch length - 15mm				Notch length - 15mm			
25S-S1	0.1408	260.24	2.02	25S7_7	0.0804	186.22	1.55
25S5_8	0.1357	249.58	1.90	25S7_8	0.1084	199.10	1.90
25S5_9	0.1123	224.15	1.84	25S7_9	0.0700	155.15	1.63
Average	0.1383	254.91	1.96	Average	0.0863	180.16	1.69
SD	0.00	7.54	0.09	SD	0.02	22.60	0.18
CV(%)	2.62	2.96	4.52	CV(%)	23.01	12.54	10.91
Notch length - 20mm				Notch length - 20mm			
25S5_10	0.1199	172.33	2.13	25S7_10	0.0754	125.02	1.73
25S5_11	0.0893	180.57	1.61	25S7_11	0.0591	122.53	1.44
25S5_12	0.0867	158.57	1.65	25S7_12	0.0597	129.60	1.40
Average	0.0986	170.49	1.80	Average	0.0647	125.71	1.53
SD	0.02	11.11	0.29	SD	0.01	3.59	0.18
CV(%)	18.72	6.52	15.93	CV(%)	14.29	2.85	11.80

g) Warm mix asphalt + 50% RAP with Sylvaroad

50R-S	Fracture energy (N.mm^{-1})	Maximum Tensile stress (kPa)	ε_{max} (%)	50R-S	Fracture energy (N.mm^{-1})	Maximum Tensile stress (kPa)	ε_{max} (%)
Notch length - 5mm				Notch length - 5mm			
50S-S5	0.3592	839.63	2.33	50S-S1	0.1412	431.91	1.76
50S7_1	0.2327	570.21	2.23	50S5_1	0.1731	436.39	1.94
50S7_2	0.1309	449.86	1.47	50S5_2	0.1337	394.92	1.74
Average	0.2409	619.90	2.01	Average	0.1494	421.07	1.81
SD	0.11	199.58	0.47	SD	0.02	22.76	0.11
CV(%)	47.48	32.20	23.54	CV(%)	14.00	5.41	6.31
Notch length - 10mm				Notch length - 10mm			
50S5_4	0.1650	456.50	1.55	50S5_10	0.0960	288.77	1.43
50S5_11	0.1840	476.09	1.72	50S7_4	0.1085	396.39	1.22
0.0000	0.0000	0.00	0.00	50S5_7	0.0949	318.67	1.32
Average	0.1745	466.29	1.63	Average	0.0998	334.61	1.32
SD	0.01	13.85	0.12	SD	0.01	55.55	0.10
CV(%)	7.68	2.97	7.19	CV(%)	7.56	16.60	7.84
Notch length - 15mm				Notch length - 15mm			
50S5_12	0.1047	329.05	1.24	50S7_5	0.1016	309.03	1.39
50S-S6	0.1930	460.22	1.69	50S7_6	0.0704	243.35	1.05
0.0000	0.0000	0.00	0.00	50S7_9	0.0876	300.05	1.12
Average	0.1488	394.63	1.47	Average	0.0865	284.14	1.19
SD	0.06	92.75	0.32	SD	0.02	35.61	0.18
CV(%)	41.97	23.50	21.82	CV(%)	18.07	12.53	14.85
Notch length - 20mm				Notch length - 20mm			
50S-S7	0.1090	257.83	1.36	50S-S2	0.0735	184.02	1.22
50S-S8	0.1154	284.24	1.34	50S5_5	0.0797	190.76	1.24
0.0000	0.0000	0.00	0.00	50S5_6	0.0741	175.59	1.26
Average	0.1122	271.04	1.35	Average	0.0758	183.46	1.24
SD	0.00	18.68	0.01	SD	0.00	7.60	0.02
CV(%)	4.02	6.89	1.07	CV(%)	4.49	4.14	1.70